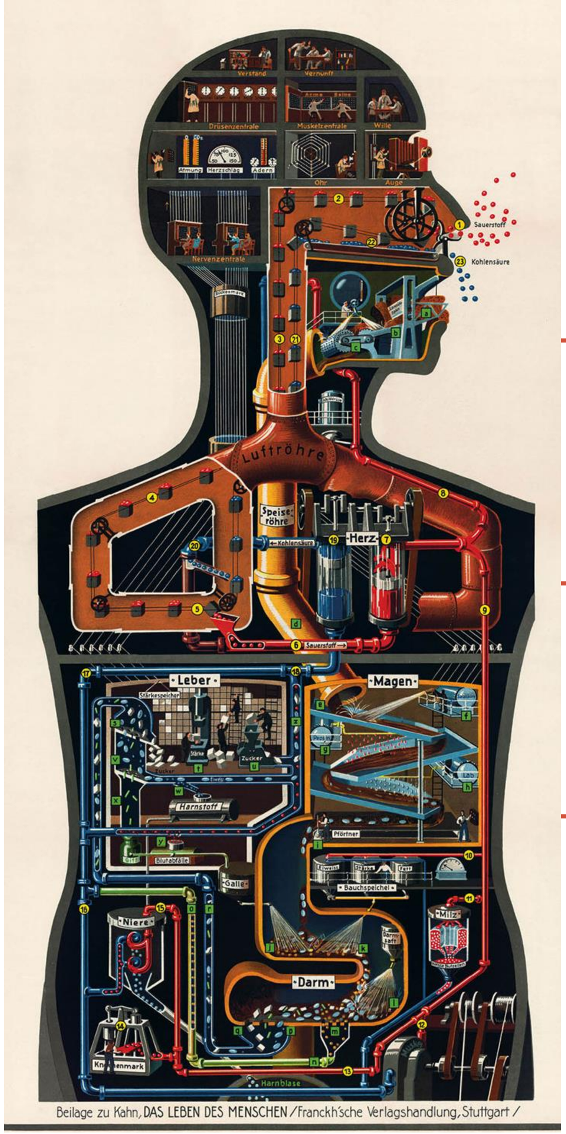



*Fritz Kahn (1888 – 1968)*

# BIOMECHANICS

## 3: Tissue and Joint Mechanics

7ο εξάμηνο

Σχολή Μηχανολόγων Μηχανικών ΕΜΠ

Διδάσκων:

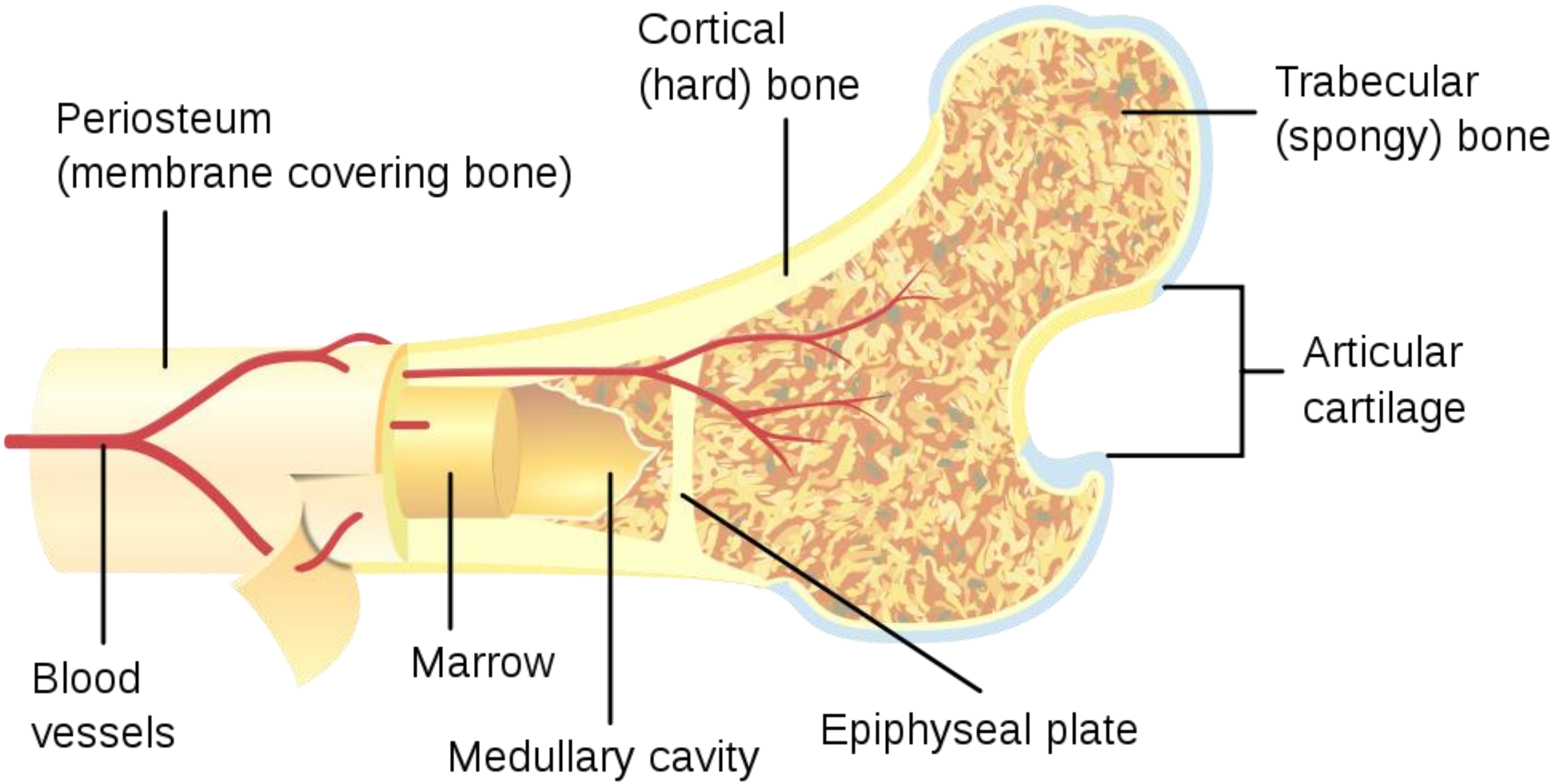
Michael Neidlin

# Content

- Tissue mechanics
  - Bone/Cartilage/Muscle/Tendon

- Joint Mechanics (Hip/Knee/Spine)
  - Anatomy
  - Physiology and Mechanics
  - Pathologies and Therapies (Devices)

# Bone (Long bone)

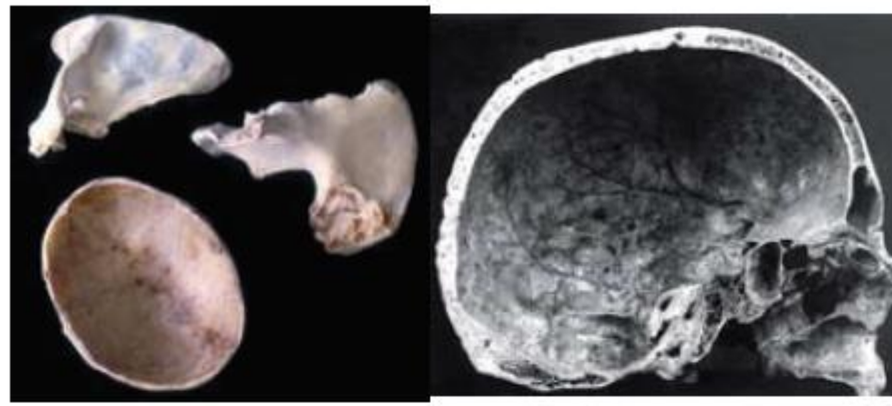



Function : Movement of joints and stability (stiffness)

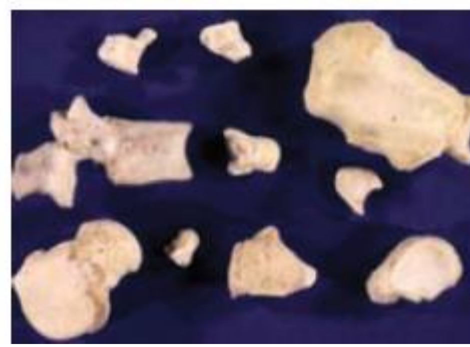
# Bone Types

Long bones - extremities

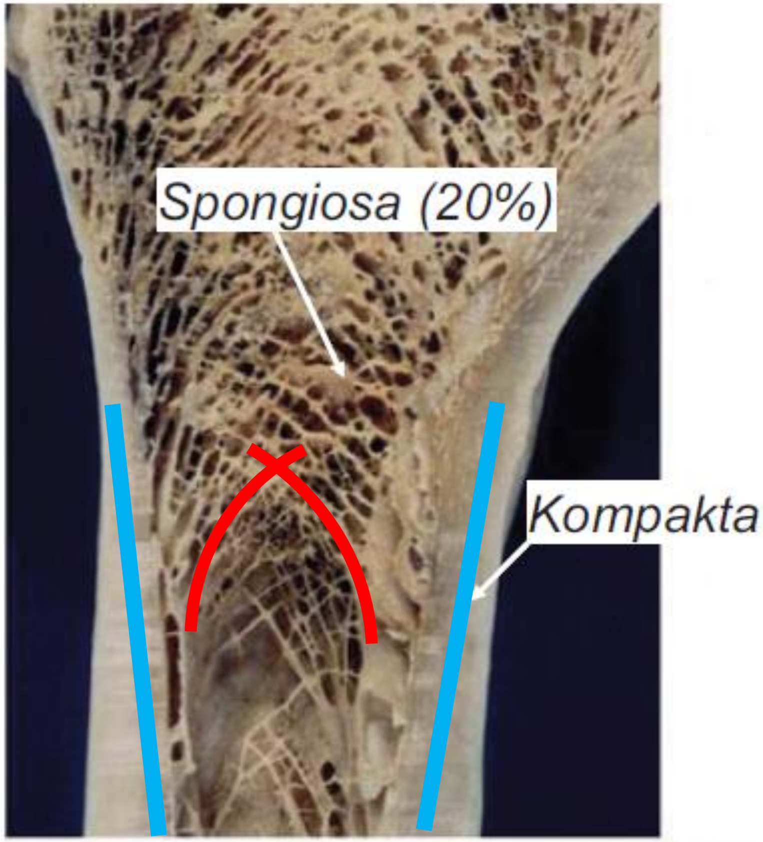
Flat bones – skull, hip



Short bones – spine, fingers



# Structural properties

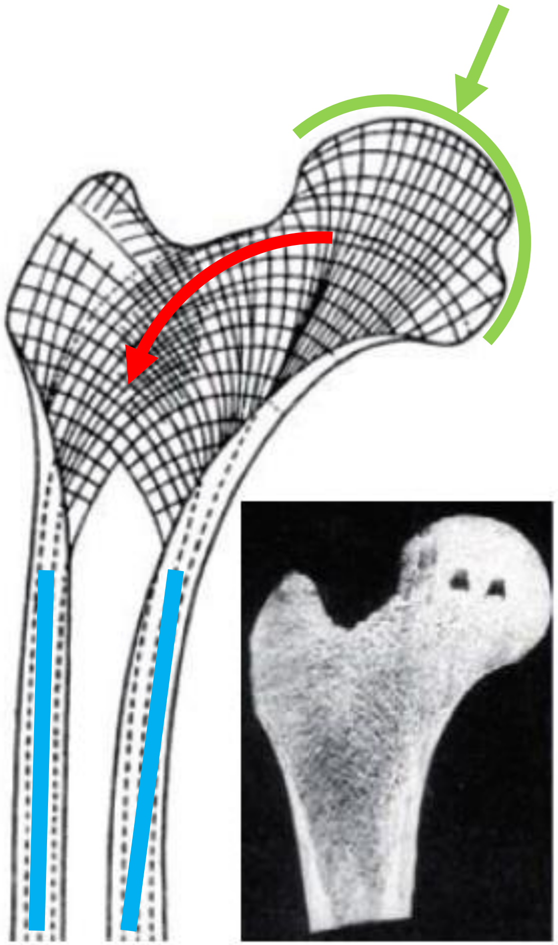



Thin compact layer

Thickening of bone head

Arc like structures of trabeculae

# Occurring mechanics cause structure



High bending stiffness and low weight:
**Dense outer layer and porous inside**

Force absorption at contact surfaces
+ big difference in compression stiffness
between bone and cartilage (130 MPa vs 35 MPa):
**Development of epiphysis**

Force translation through bone
**Development of trabeculae**
**orientated in the principal stress directions**

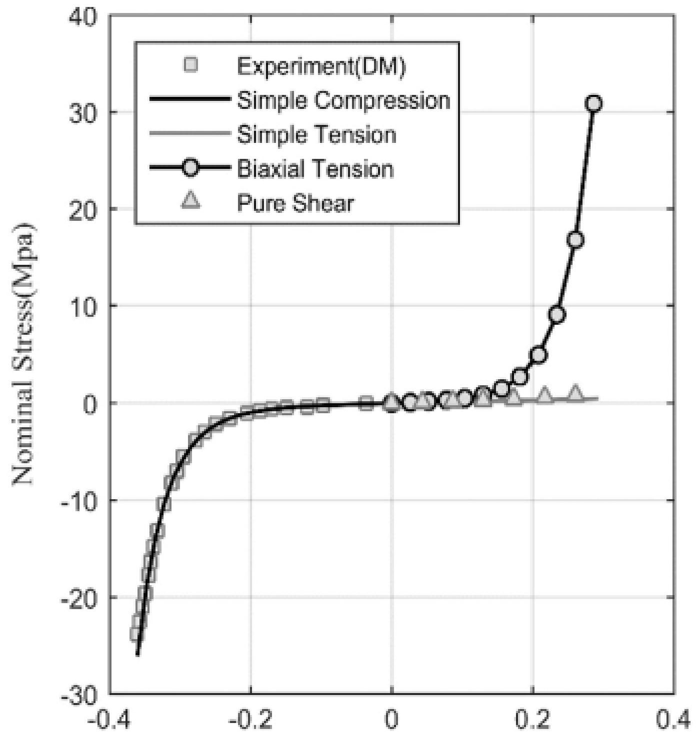
# Modeling & Remodeling

- Wolff's Law (Modeling) : "Bone adapts to the load under which it is placed"

- Remodeling : Change of bone components without change of shape. E.g. after trauma

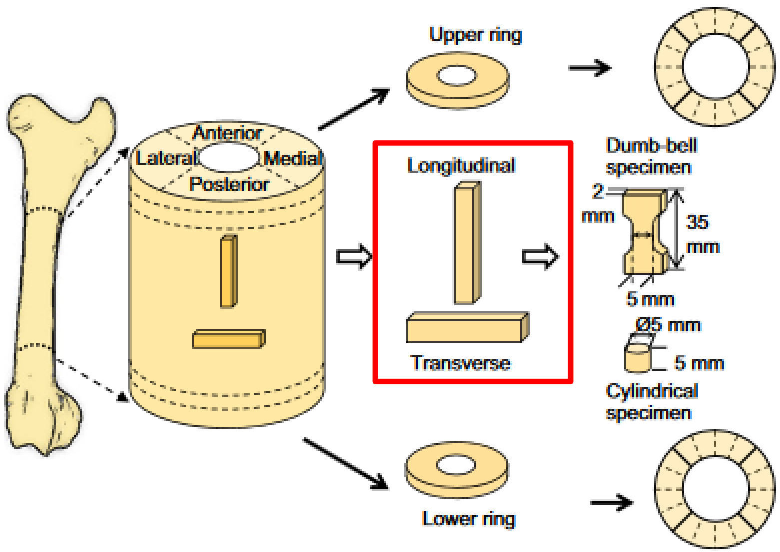
# Mechanical properties of bone

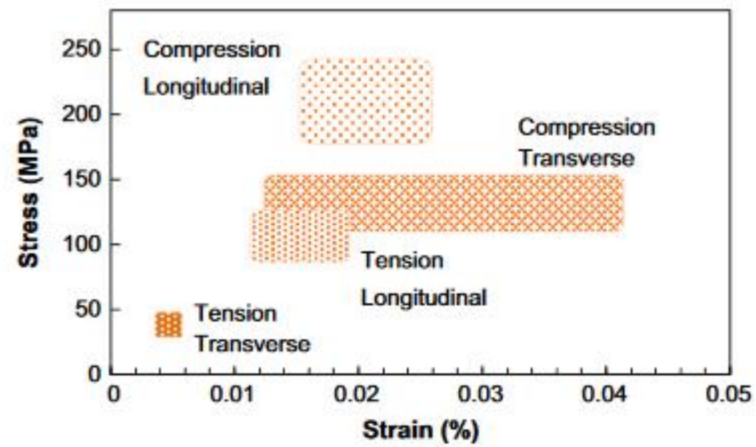
- Non-elastic (hyperelastic) behavior



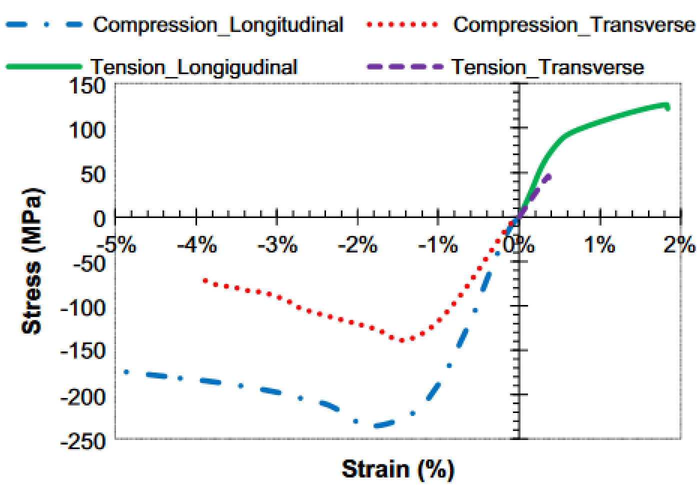

Hosseinzadeh, M. et al. 2016

# Anisotropy of cortical bone



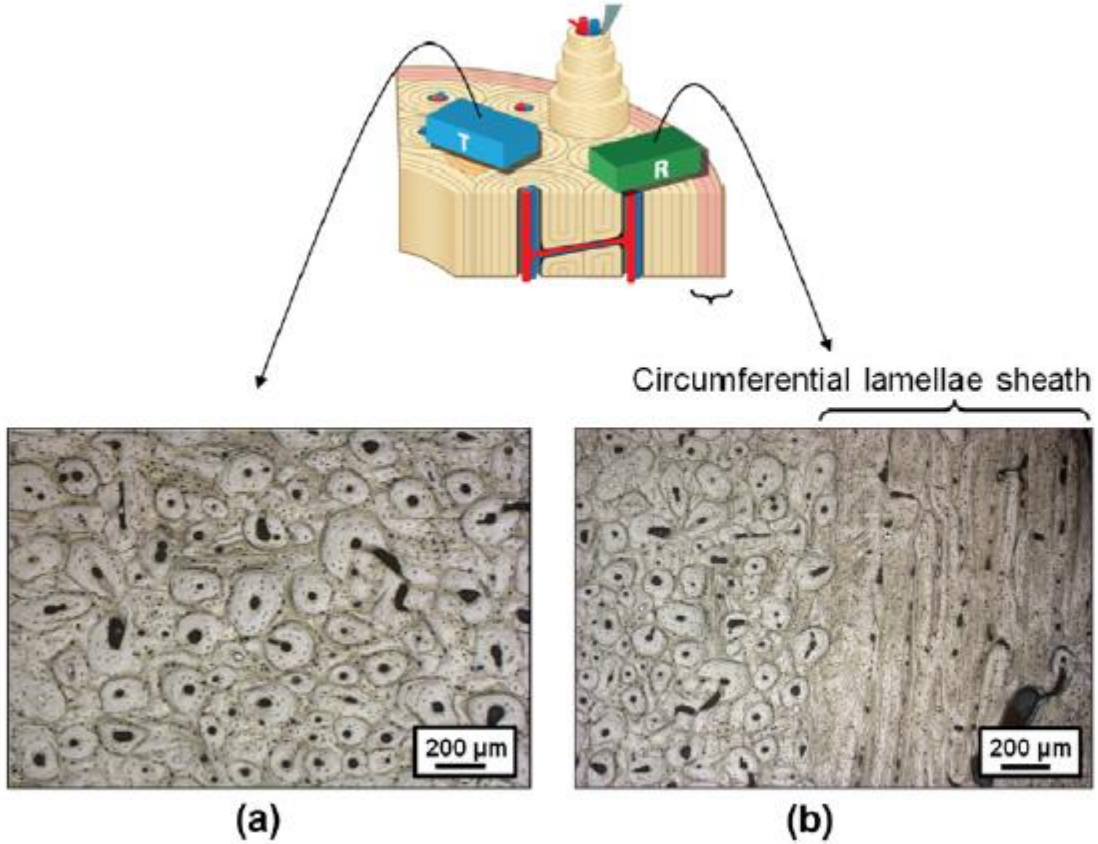

Failure regions after ultimate compression tests




Different stress-strain behaviour

Li et al.2013

# Microstructure in radial and transverse direction




Novitskaya et al.2011

# Mechanical properties of cortical bone

- Anisotropy
  - Young's modulus in longitudinal direction 17 GPa
  - Young's modulus in transversal direction 11 GPa

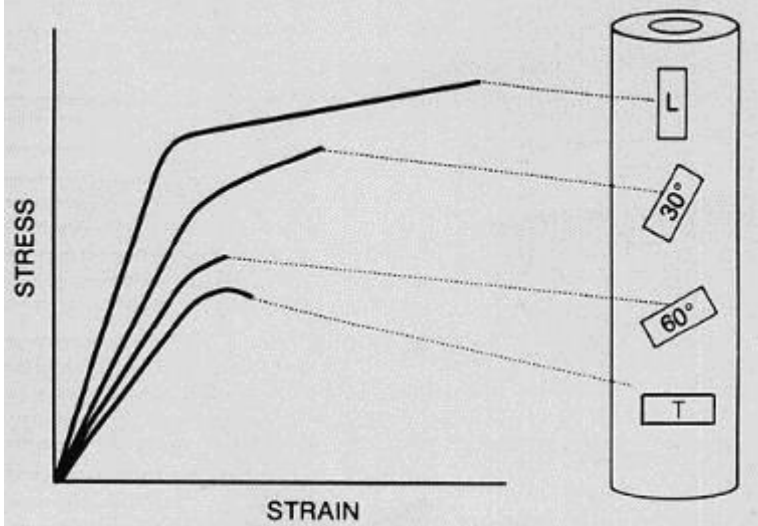
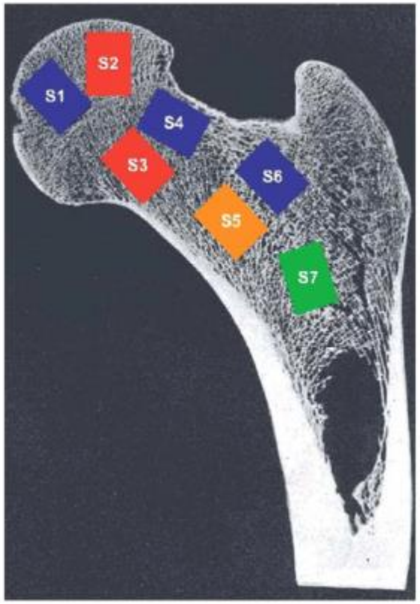
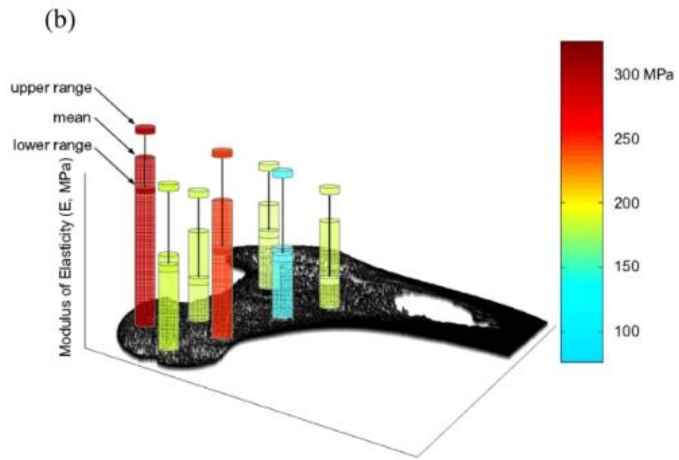



**FIG. 12-8** Anisotropic behavior of cortical bone specimens machined from a human femoral shaft and tested in tension. The orientation of load application—longitudinal (*L*), tilted 30° with respect to the bone axis, tilted 60°, and transverse (*T*)—strongly influences both the stiffness and the ultimate strength. (Frankel VH, Nordin M: Basic Biomechanics of the Skeletal System, p. 22. Philadelphia, Lea & Febiger, 1980)

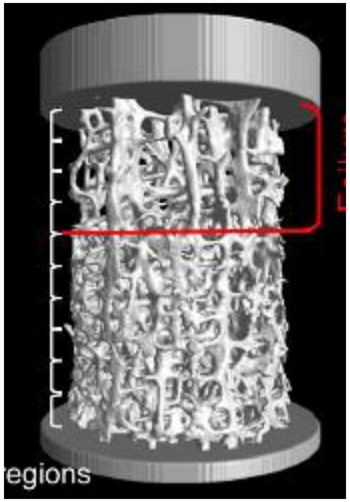
# Mechanical properties of spongiosa (trabecular bone)




Oftadeh et al.2015

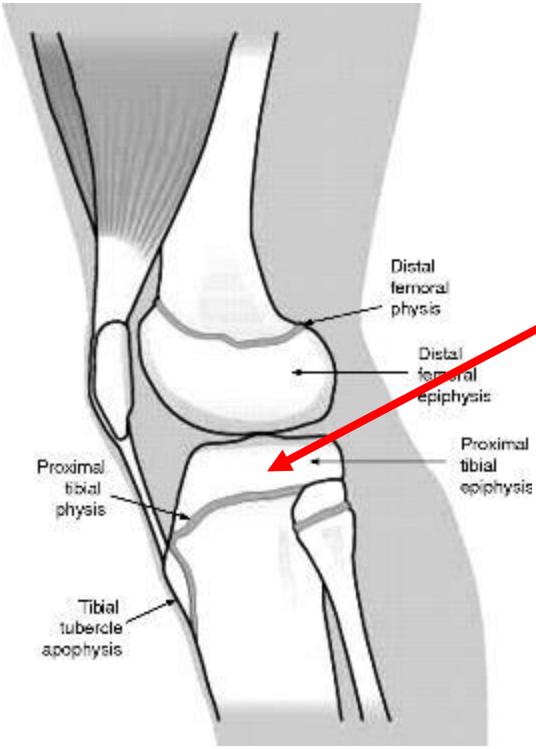



Foam like structure with mechanical properties dependent on sample location




µCT scan

# Isotropic or anisotropic?





J. L. Williams

J. L. Lewis

Departments of Civil Engineering and Orthopaedic Surgery, Northwestern University, Evanston, Ill. 60201

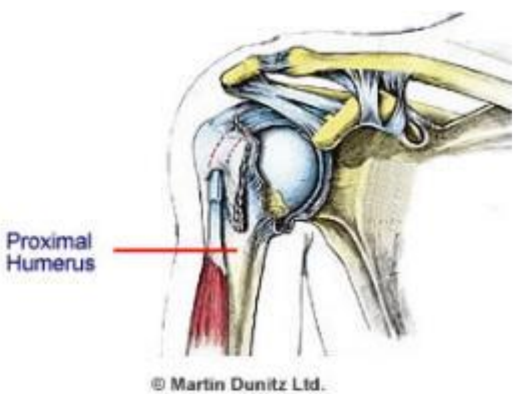

## Properties and an Anisotropic Model of Cancellous Bone From the Proximal Tibial Epiphysis


*An investigation has been made of the source and magnitude of anisotropic material properties of cancellous bone in the proximal epiphysis of the human tibia. Results are reported for stiffness measurements made in three orthogonal directions on 21 cubes of cancellous bone before testing to failure along one of the three principal axes. The structure is approximately transversely isotropic. Strength and stiffness are linear with area fraction for loading along the isotropic axis. Strength is proportional to stiffness for all directions. A finite element model is proposed, based on experimental observations, which enables one to predict the elastic constants of cylindrically structured cancellous bone in the tibia from morphological measurements in the transverse plane.*


Williams et al .1982

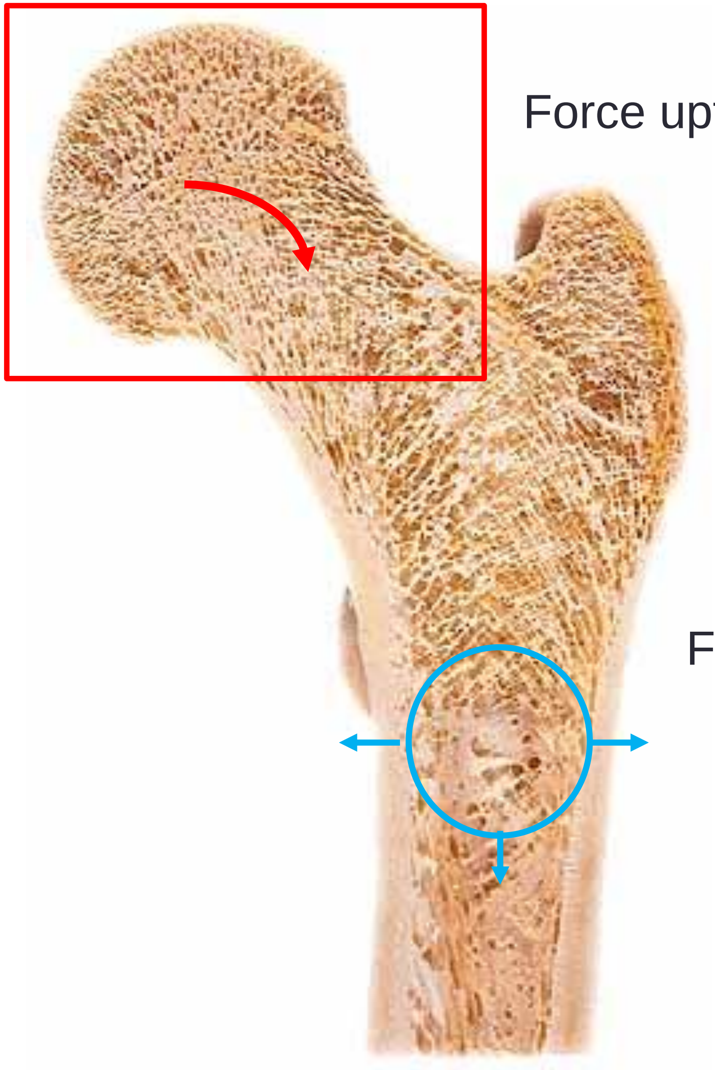
| Cube no. | $E_1$ ($MN/m^2$) | $E_2$ ($MN/m^2$) | $E_3$ ($MN/m^2$) |
|---|---|---|---|
| | | Plate-rod cubes | |
| PR 1 | 41.7 | 22.6 | 279.9 |
| PR 2 | 95.1 | 74.5 | 457.8 |
| PR 3 | 130.3 | 47.1 | 213.7 |
| PR 4 | 79.3 | 36.2 | 373.0 |
| PR 5 | 32.2 | 34.9 | 265.4 |
| PR 6 | 47.9 | 20.2 | 244.1 |
| PR 7 | 58.1 | 17.0 | 193.0 |
| PR 8 | 43.7 | 13.2 | 203.4 |
| PR 9 | 58.7 | 9.0 | 363.3 |
| PR 10 | 41.0 | 10.4 | 123.4 |

10x




From this part of the bone Kaplan et al.1985 found isotropic behavior of bone 7.6+/-2.2 MPa (tensile strength) and 12.4+/-3.4 MPa (compression strength)

# Summary anisotropy/isotropy spongiosa

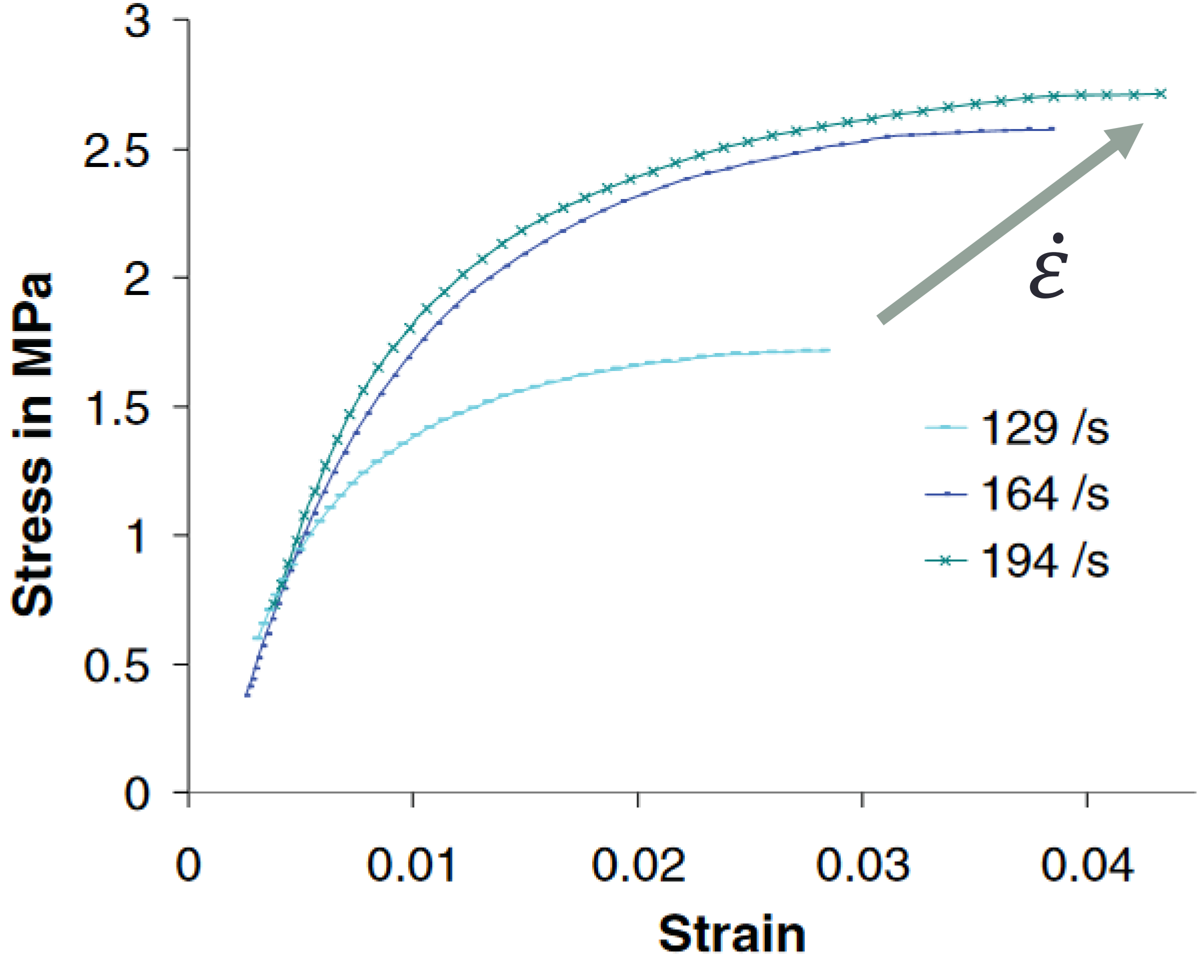


Force uptake and translation

Force distribution

# Mechanical properties of bone

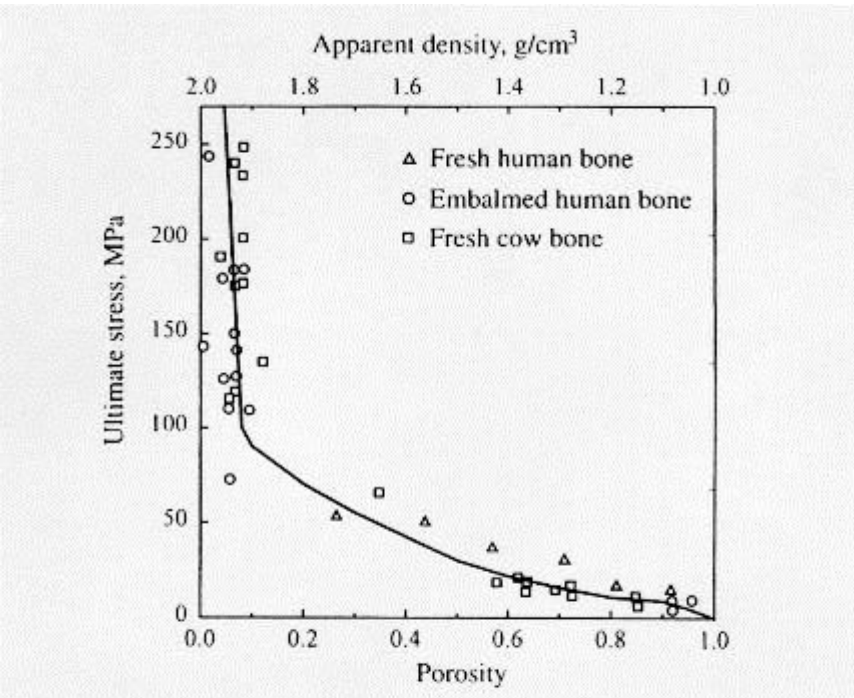
- Viscoelasticity: stress depends on strain rate

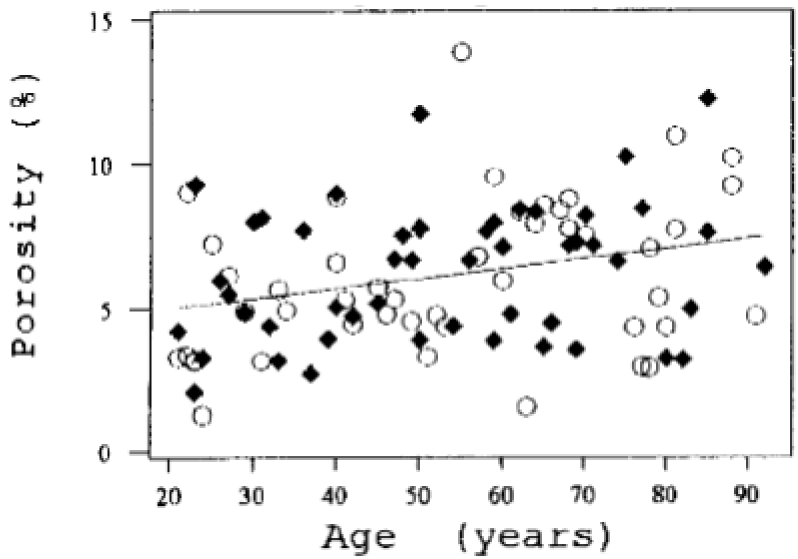



Kranthi Teja et al. 2013

# Mechanical properties of bone

- Ultimate stress decreases with porosity, porosity increases with age




Stein et al. 1999

Transmitted Light Image before Staining

pores in cortical bone slices of 96-year old woman

Mirzaali et al.2015

# Questions?

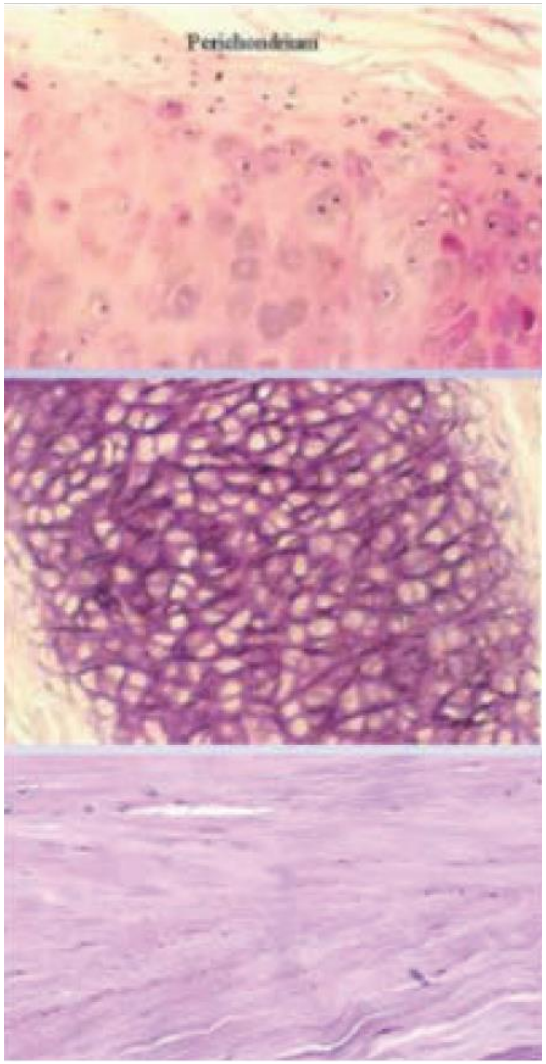
# Cartilage

**Hyaline cartilage**
- Covers joints (**articular cartilage**)
- Ribs, nose...

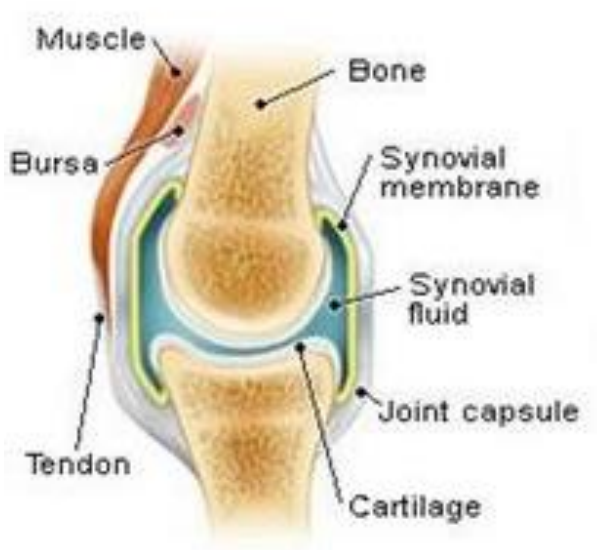
**Elastic cartilage**
- Ears
- Larynx

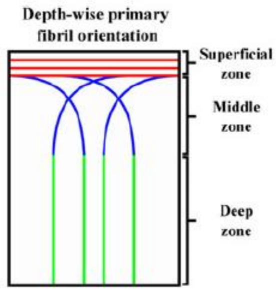
**Fibrocartilage**
- Intervertebral discs
- Menisci

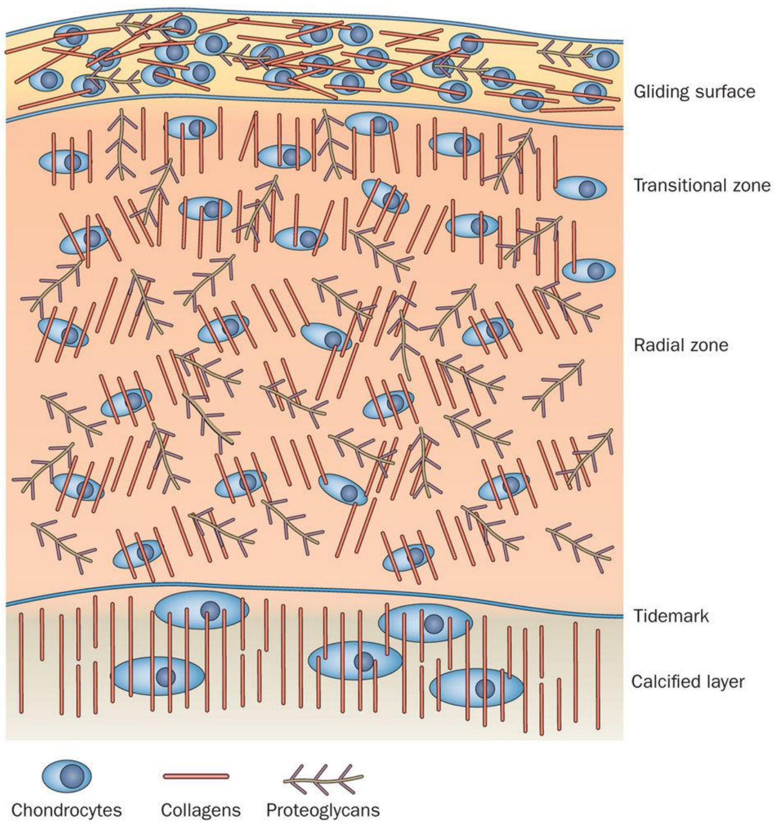
Function (articular cartilage): Allow joint movement by providing a low-friction environment



# Articular cartilage

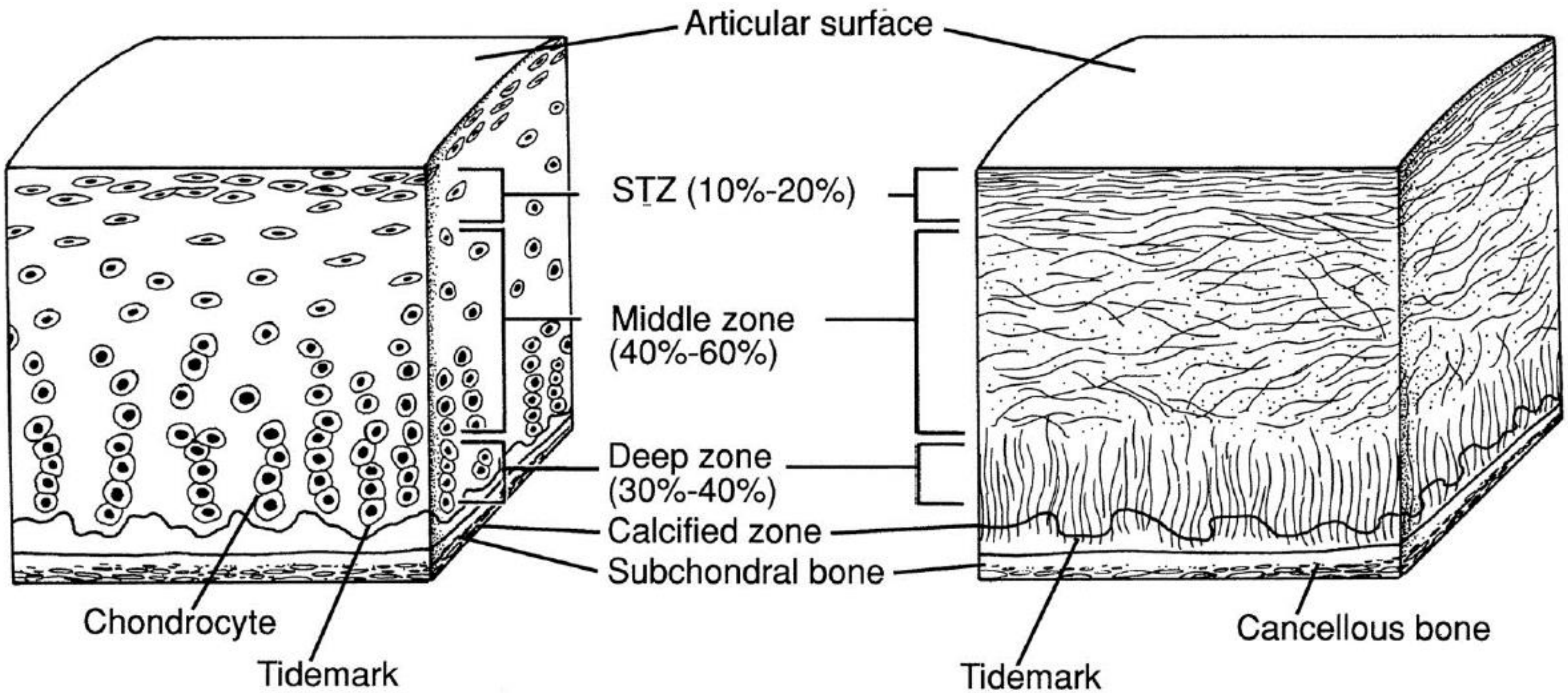


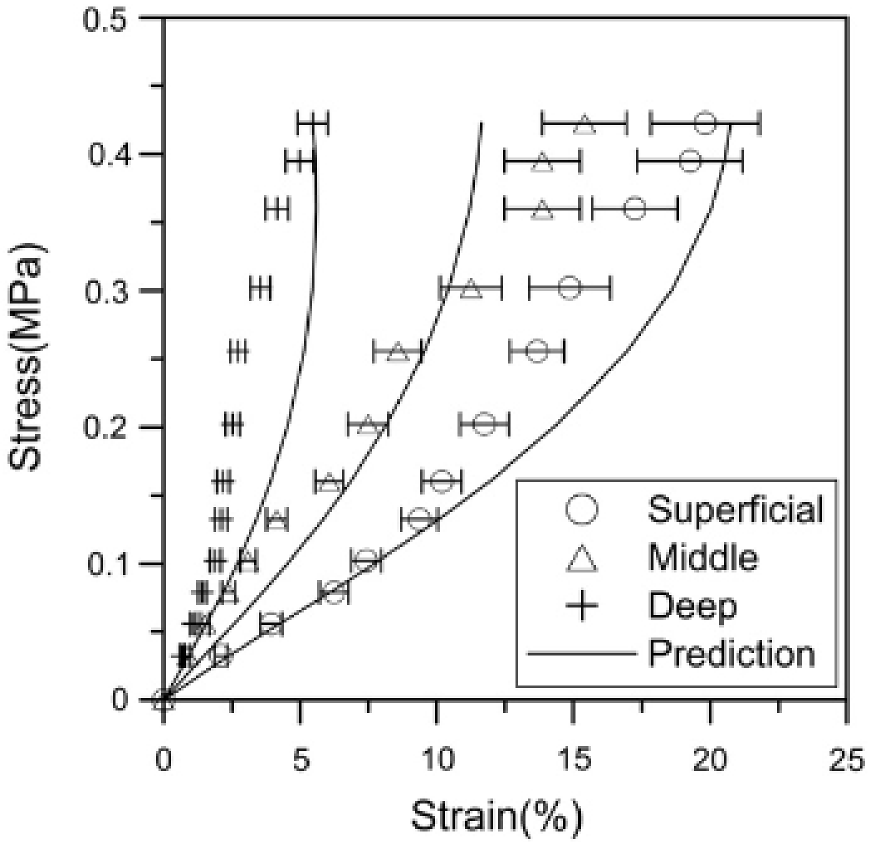

Extracellular matrix (collagens and proteoglycans) : structural support element
Chondrocyte: Cartilage cells that synthesize and maintain ECM
**Cell communication and intracellular signaling is of crucial importance!**
**(Systems biology & Biomechanics in parallel)**

# Articular cartilage



# Mechanical properties of cartilage

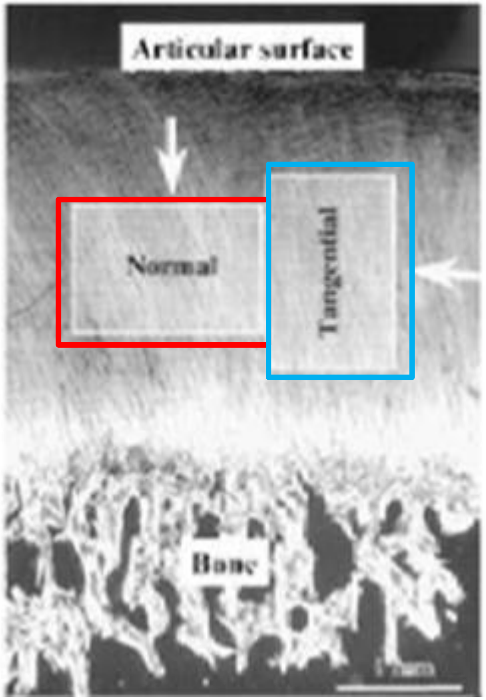
- Hyperelastic and layer dependent

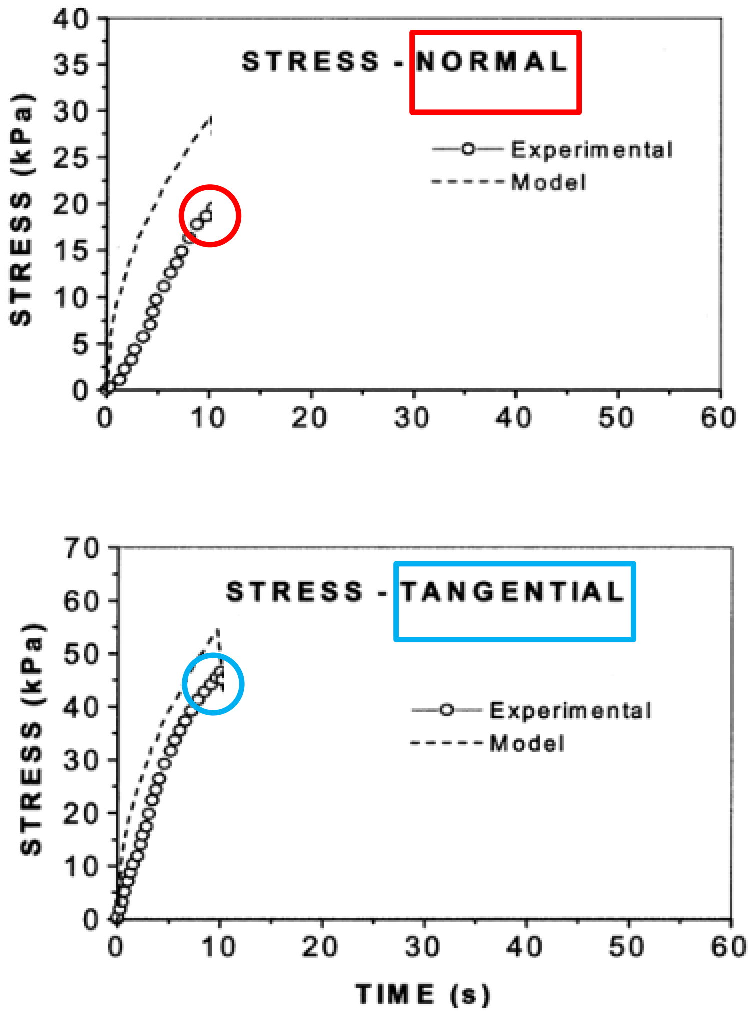



Gao et al. 2014

# Mechanical properties of cartilage

- Anisotropic

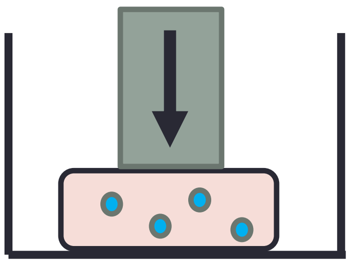


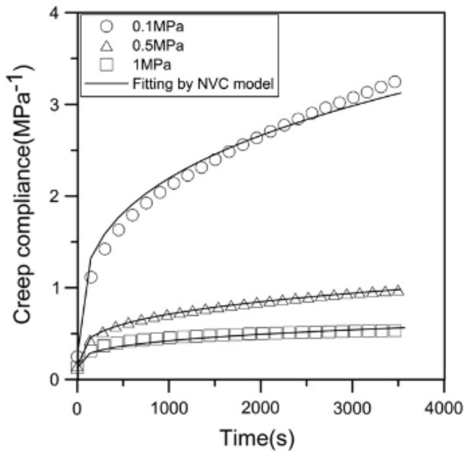




Jurvelin et al. 2003

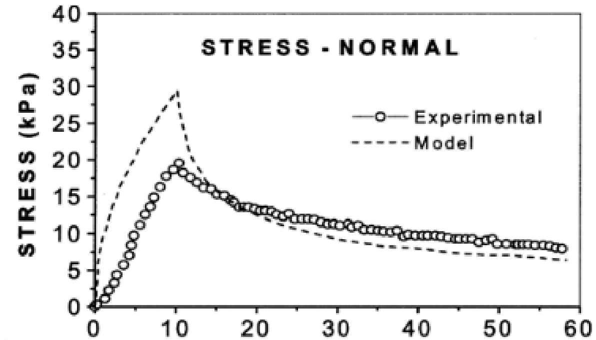
# Mechanical properties of cartilage

- Bi-phasic : Sponge-like material with solid phase and liquid phase – Poroviscoelastic material

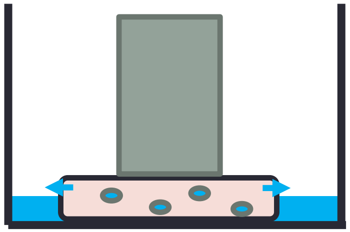


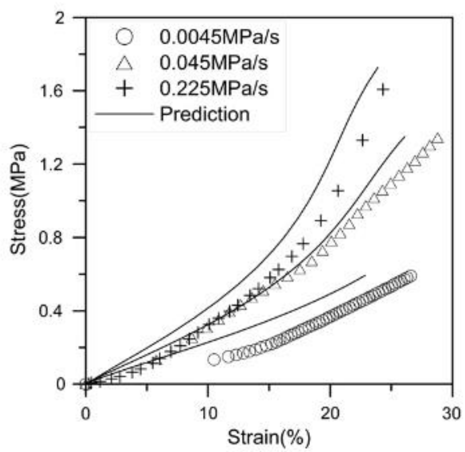


Creep

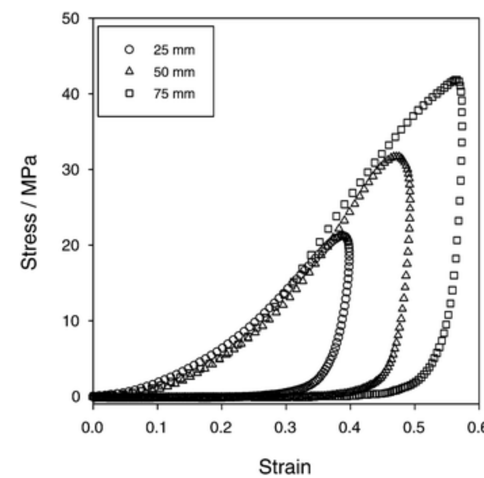


Relaxation





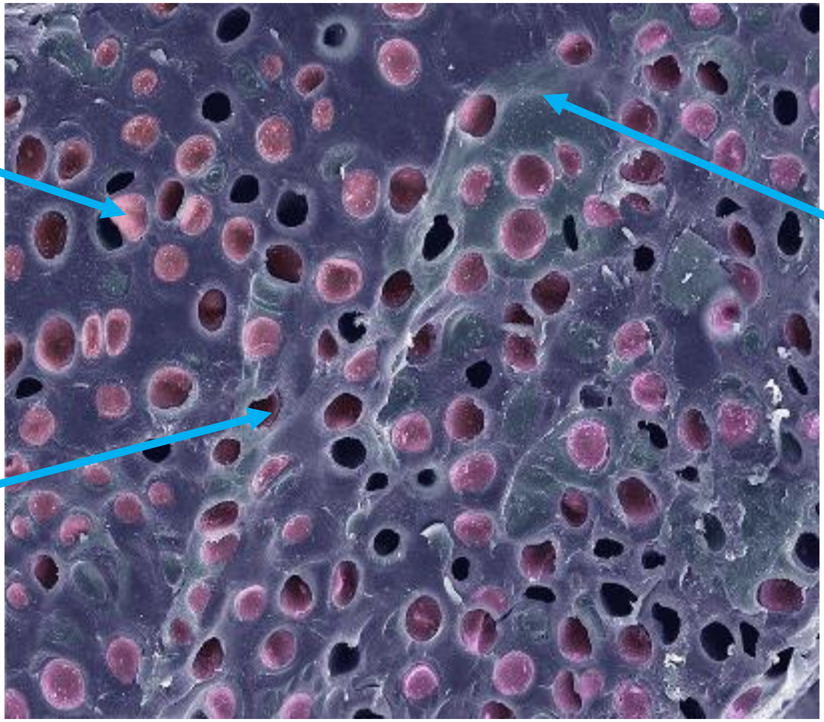
Rate dependence



Hysteresis

Gao 2014, Jurvelin 2003, Edelsten 2010

# Quantification of mechanical properties

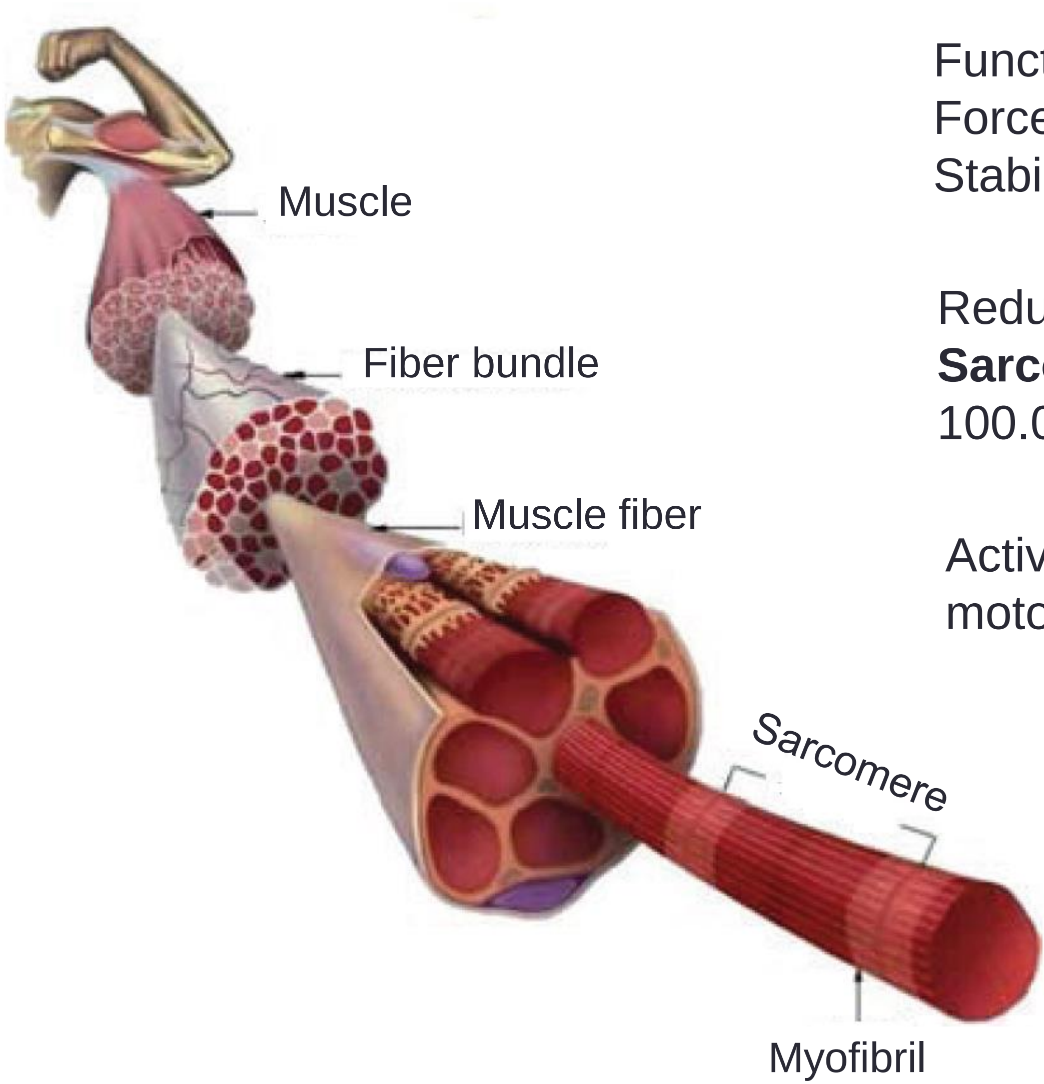



Cartilage is best represented by a biphasic model
with elastic modulus **E** and hydraulic permeability **k** (and porosity Φ)

They depend on tissue state and loading

# Questions?

# Skeletal muscles

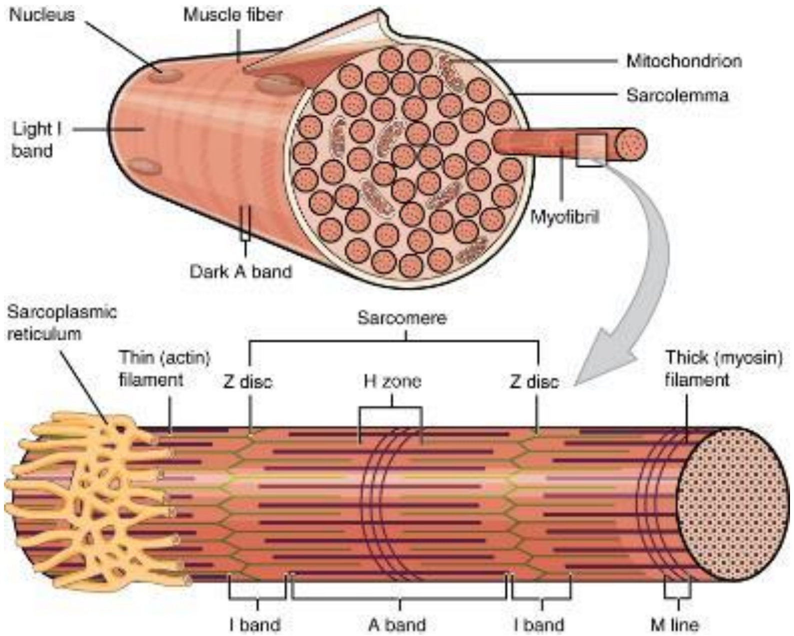


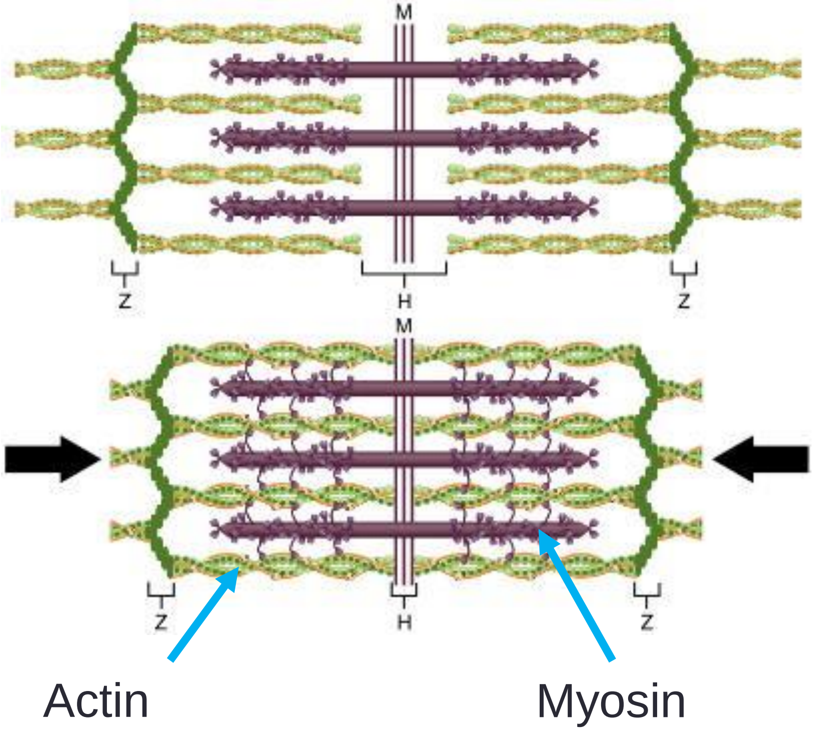

Function:
Force creation for movement of bones
Stability

Redundant structure,
**Sarcomere** as functional unit
100.000 in biceps

Activation upon stimulation by motoneuron

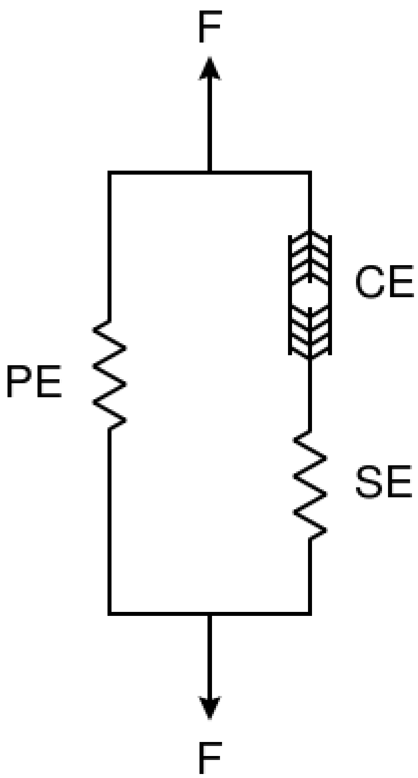
# Sarcomere

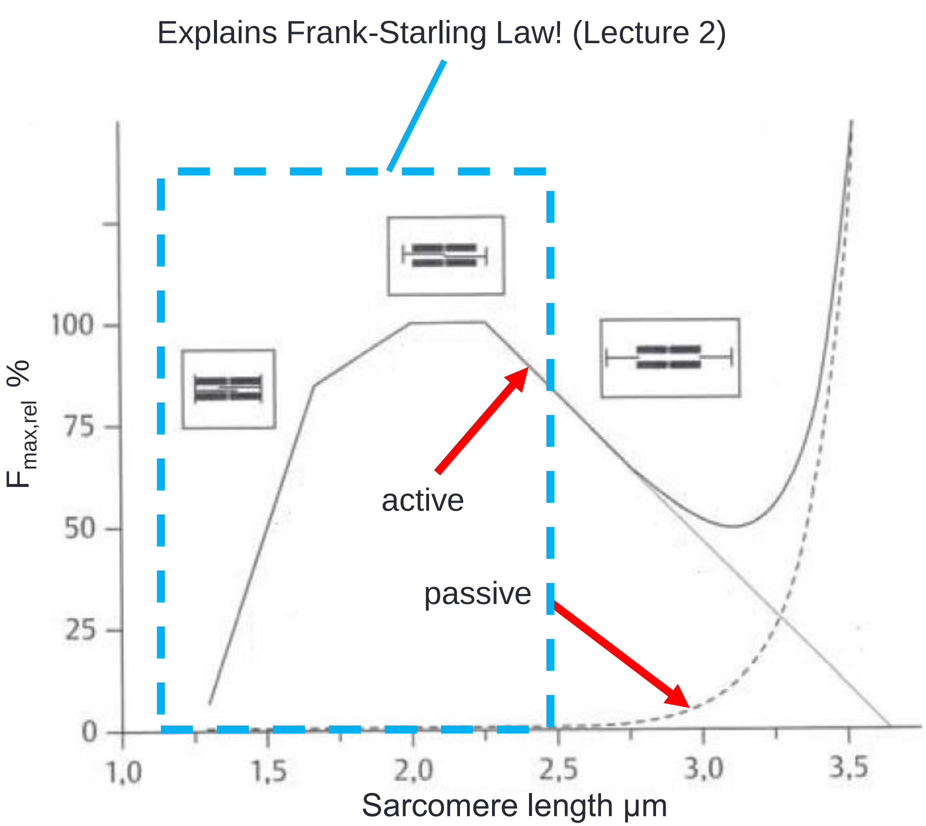



Myosin “heads” protrude along actin filaments ➔ contraction

# Hill’s muscle model



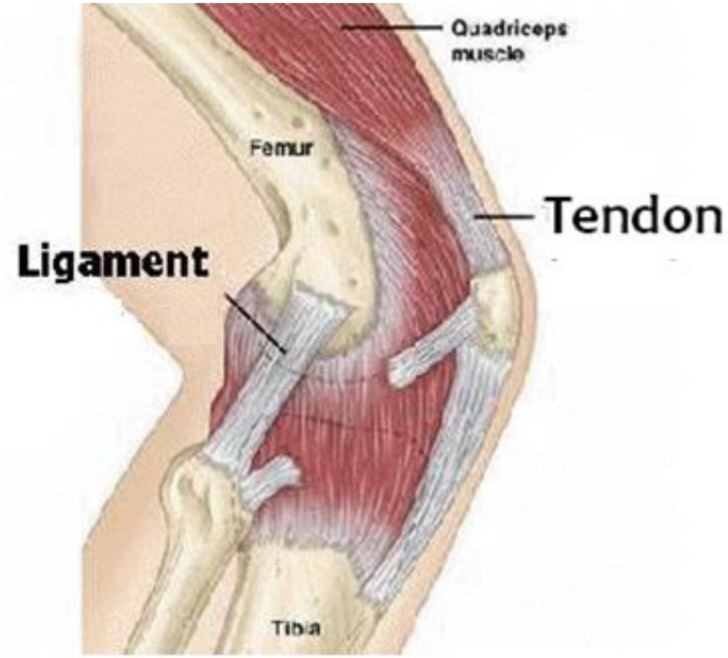

F: Muscle force
CE: Contractile element – Sarcomere
SE: Series element – Elasticity of tendons/myofibrils (depends on elongation)
PE: Parallel element – Soft tissue behavior (passive force)

# Myosin movement

https://www.youtube.com/watch?v=qDbYkv1sPpM

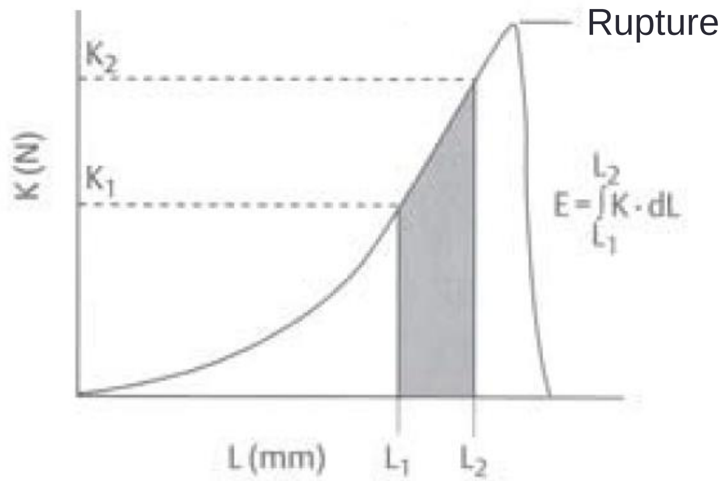
Affinity dependent binding (association and dissociation of ADP and ATP) produces the motion
In the end atomic force microscopy videos

# Tendons and ligaments




**Tendons:**
Force translation from muscle to bone. Energy conservation. Higher stiffness ➔ thinner

**Ligaments:**
Stability of joints



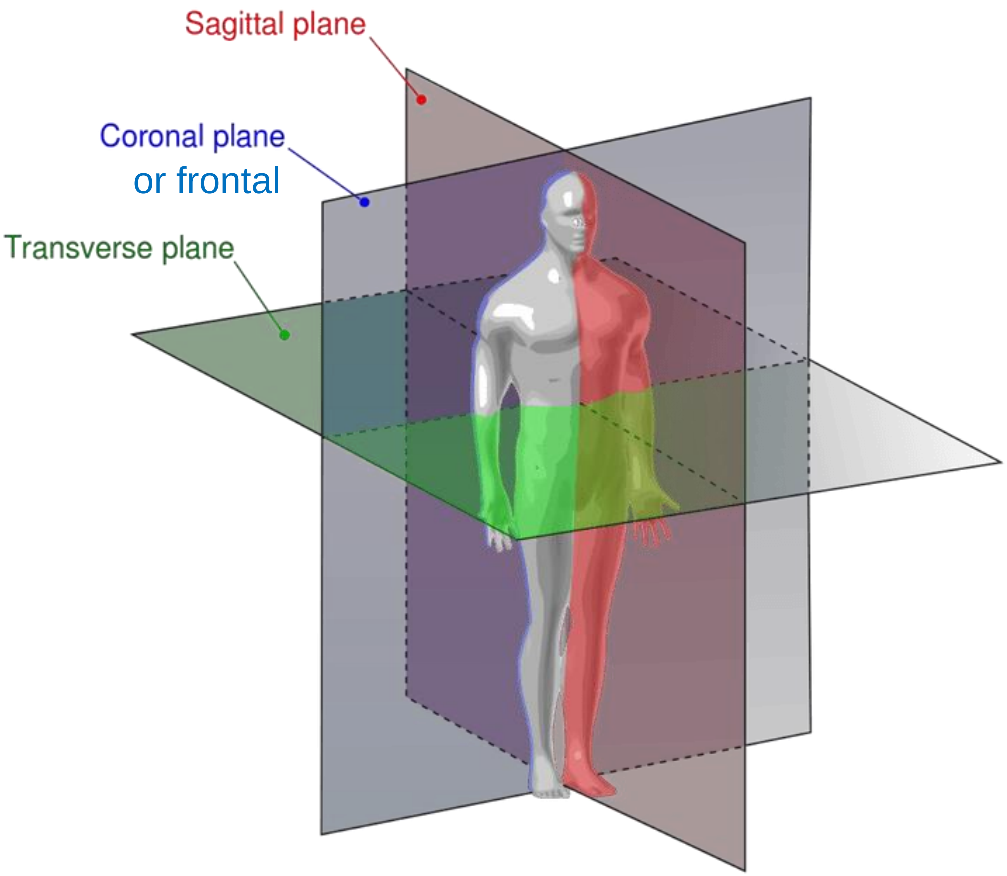

$\sigma_{max}$= 100MPa
$\varepsilon_{max}$=10%

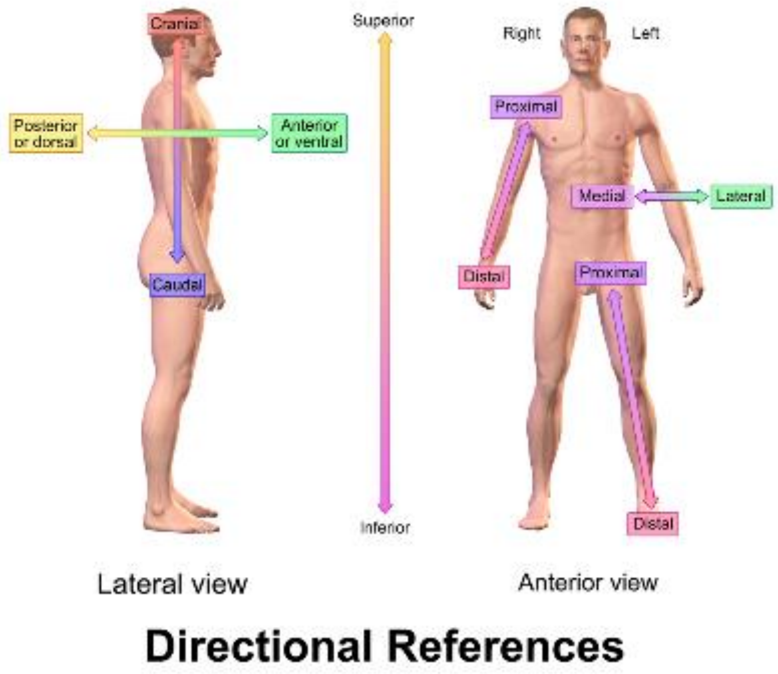
# Summary

- Bones – Moving members of joints. Modeling/Remodeling
- Cartilage – Allows joint movement,
- Muscle – Locomotion, only tension forces
- Tendons/Ligaments – Stability and force translation

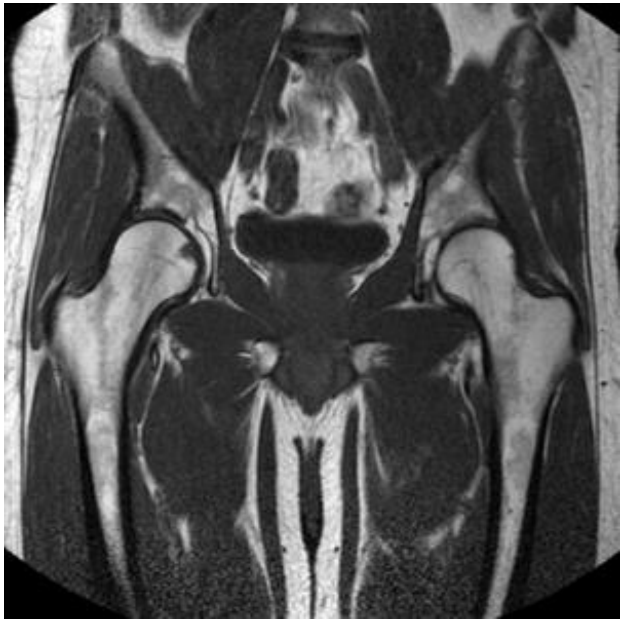
# Questions?

# Joint Mechanics – Anatomical planes

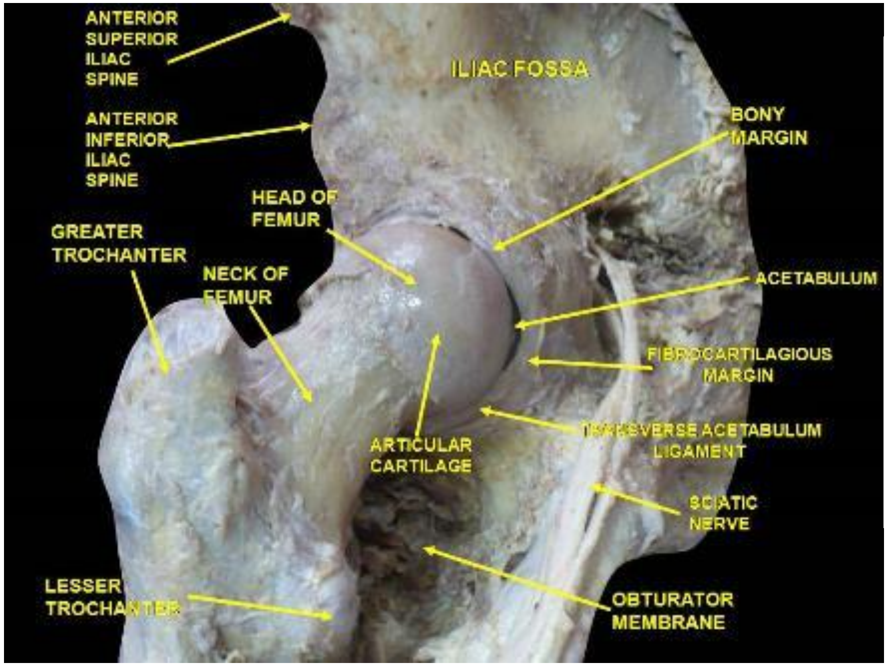


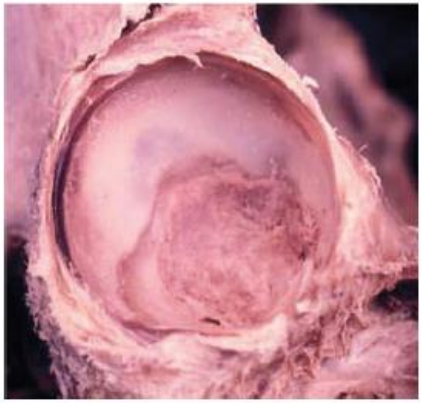
# Hip Joint Anatomy



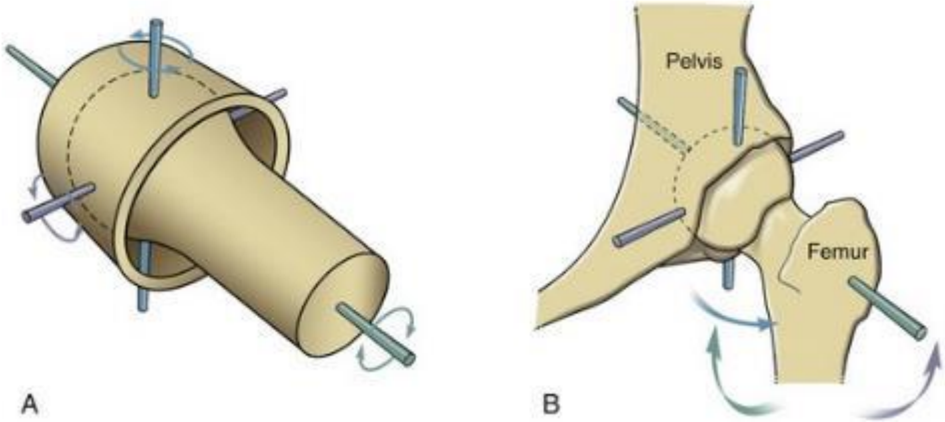
# Acetabulofemural joint




*Acetabulum*

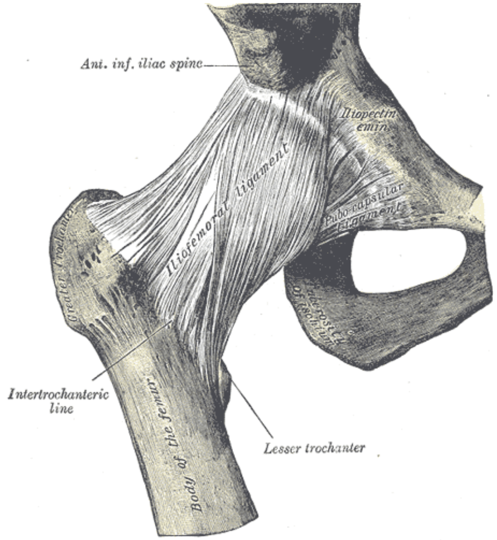


*Femur*

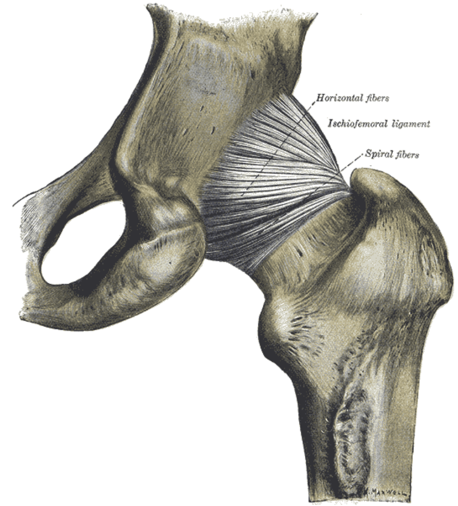



Mechanical analogy:
**spheroidal joint**

# Muscles and ligaments




Anterior




Posterior

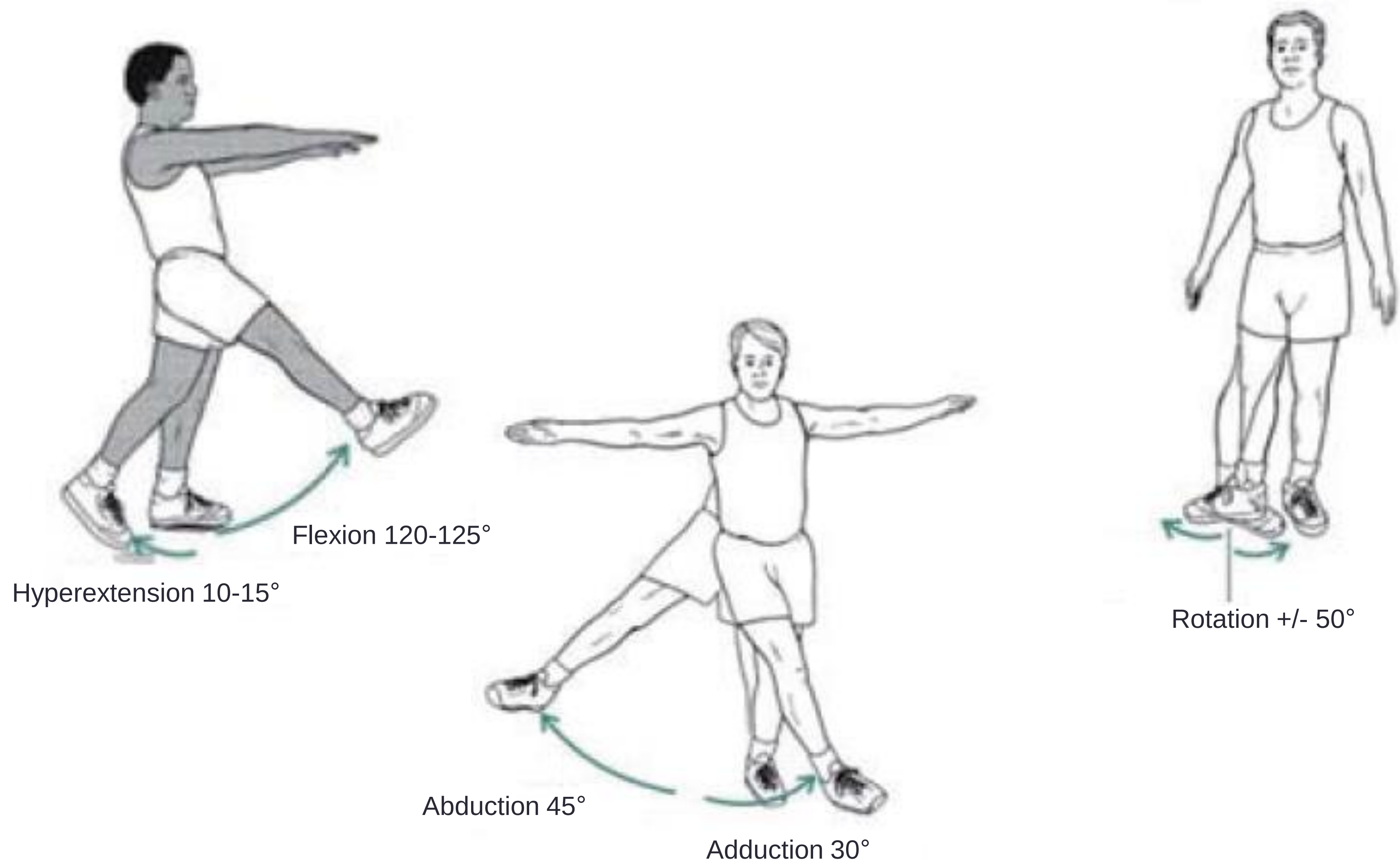
Flexors

Extensors

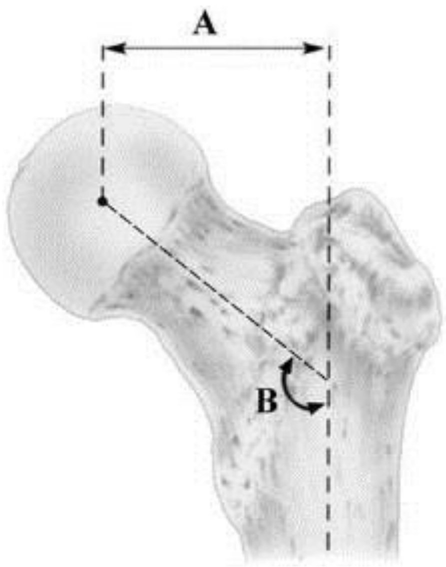
Abductors

Adductors

# Movement capabilities



# Functional parameters – Femur head

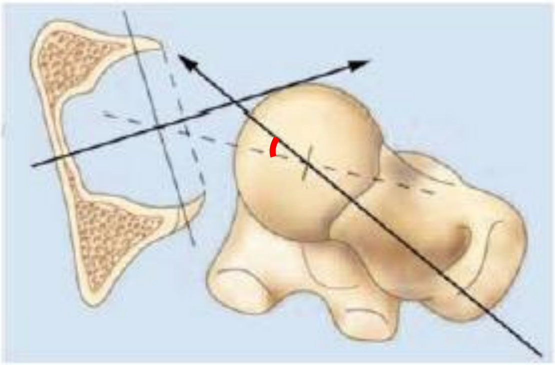



Coronal plane

A : Offset (30-60 mm)

B: caput-collum-diaphyseal or **CCD** angle (120°-135°)

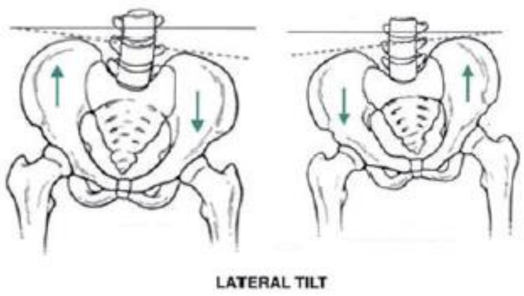
C: Ante version (12°-14°)

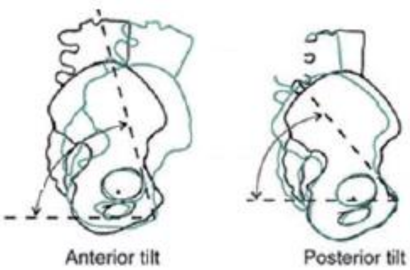


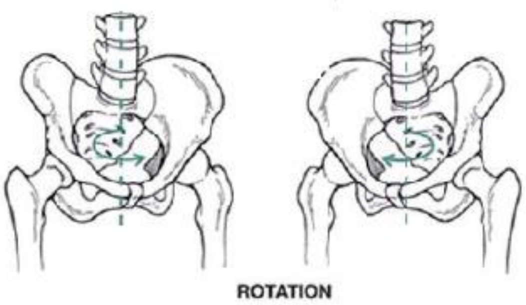
Transversal plane

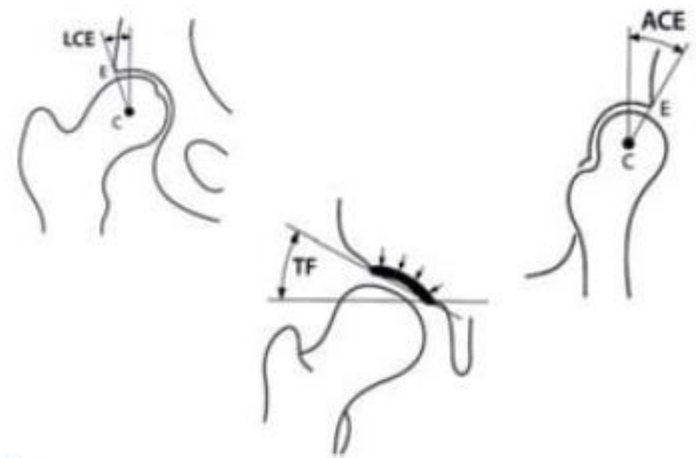
C

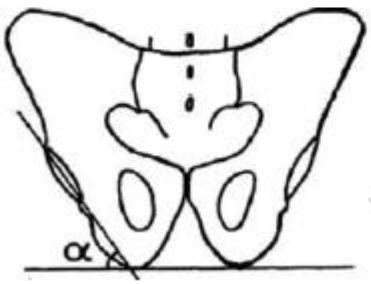
# Functional parameters - Hip



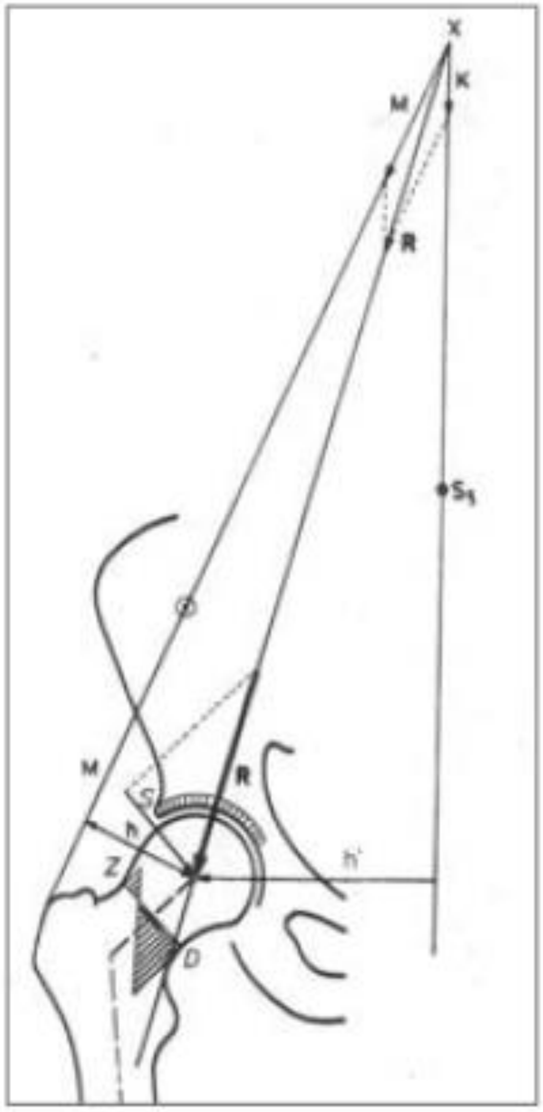




Inclination

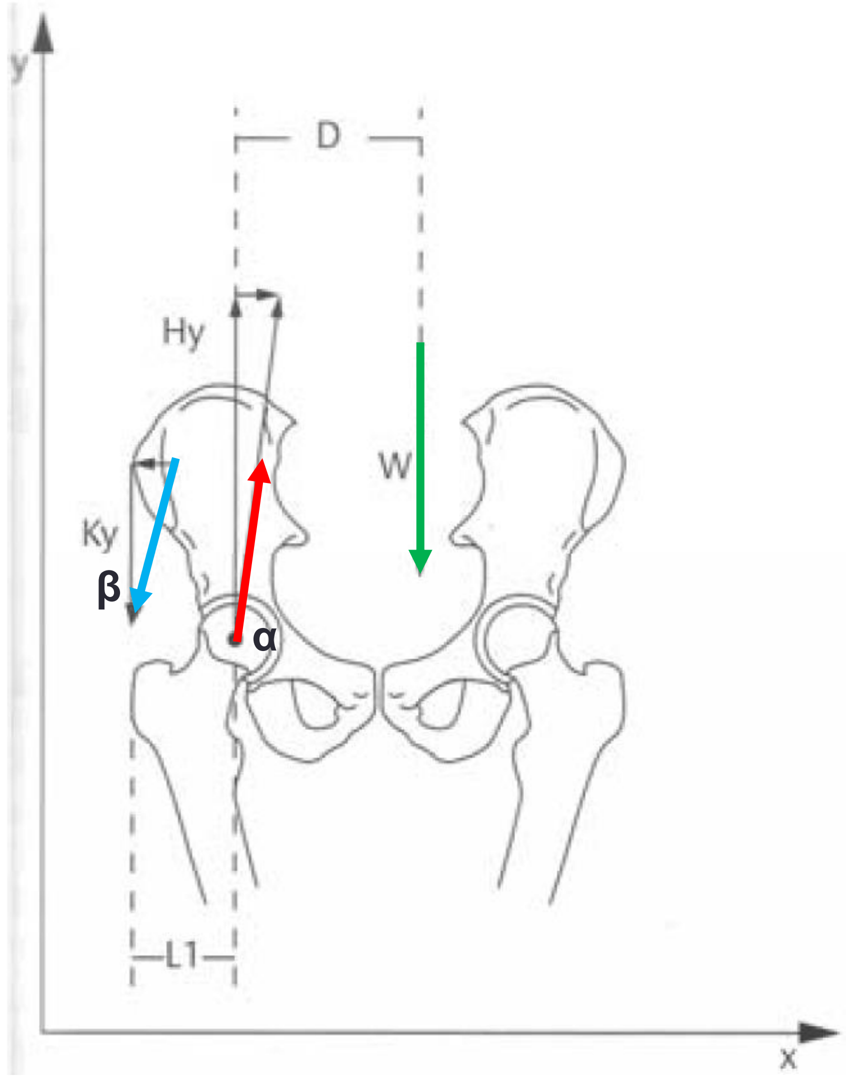
Many angles and measurements possible ➔ Each has an influence on gait and possible pathologies!

# Mechanics - Preliminaries




- High loads (2 BW (stand) – 10 BW (run))
- High frequencies – 3 Mio steps p.a.
- Pathologies: i.a. failure of form and function of femur head and acetabulum

# Biomechanics – 2D – standing phase during walk



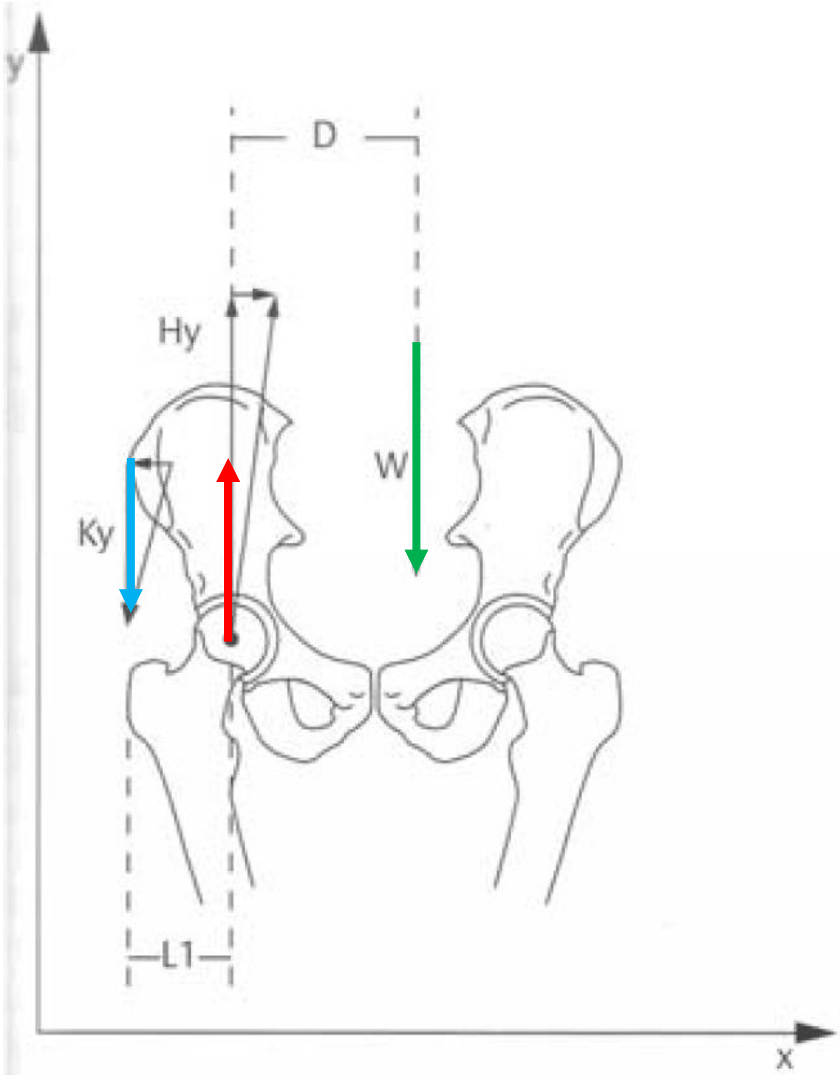

Body weight **W** at center of mass with distance **D**

Joint force **H** under angle **α** (normal to acetabulum)

Muscle force **K** under angle **β** (orientation of abductor tendon, β = 15°)

Offset $\mathbf{L_1}$

# Calculation of Forces




$$\sum M_i = 0 = K_y \cdot L_1 - W \cdot D$$

$$\Rightarrow K_y = (W \cdot D) / L_1$$

$$\sum F_y = 0 = -K_y - W + H_y$$

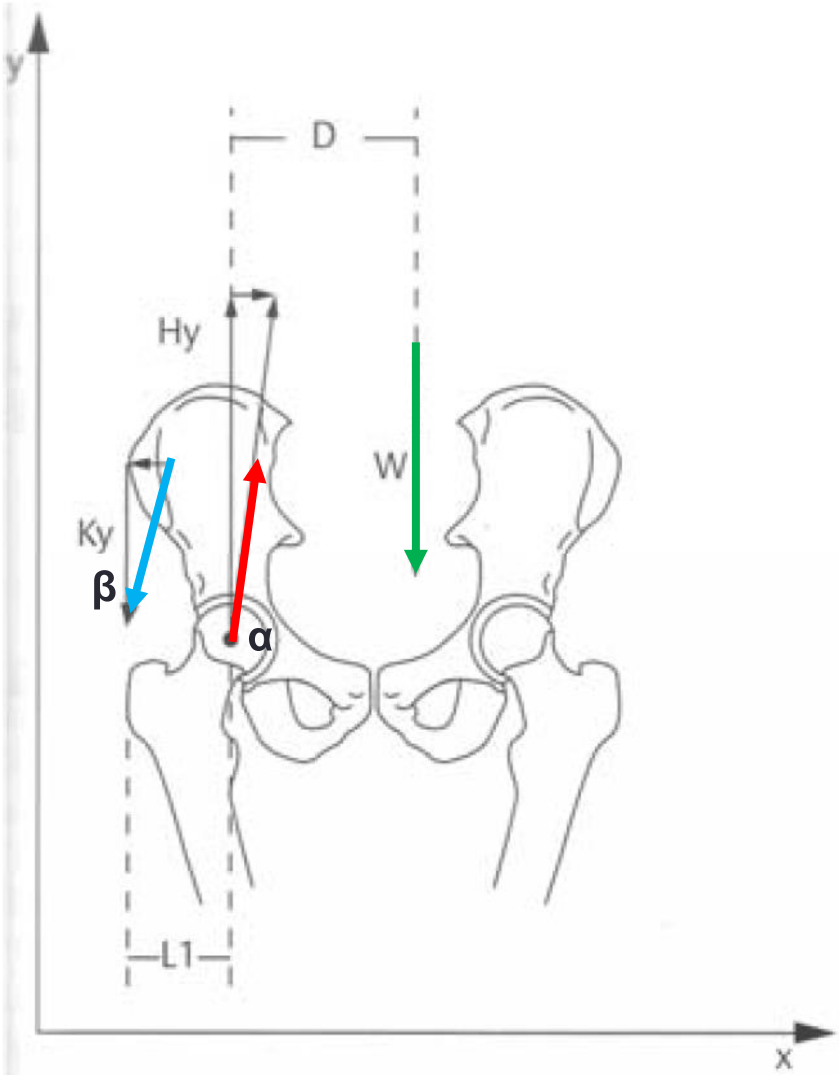
$$\mathrm{H_y} = K_y + W = W(1 + D / L_1)$$

$$D \approx 2 \cdot L_1$$

$$W = 0{,}8 \cdot m \cdot g$$

$$\Rightarrow H_y = 2{,}4 \cdot m \cdot g$$

# Calculation of angles/resulting forces




$$K_x = K_y \cdot \tan\beta$$

$$H_x = K_x = D / L_1 \cdot W \cdot \tan\beta$$

$$H = \sqrt{H_x^2 + H_y^2}$$

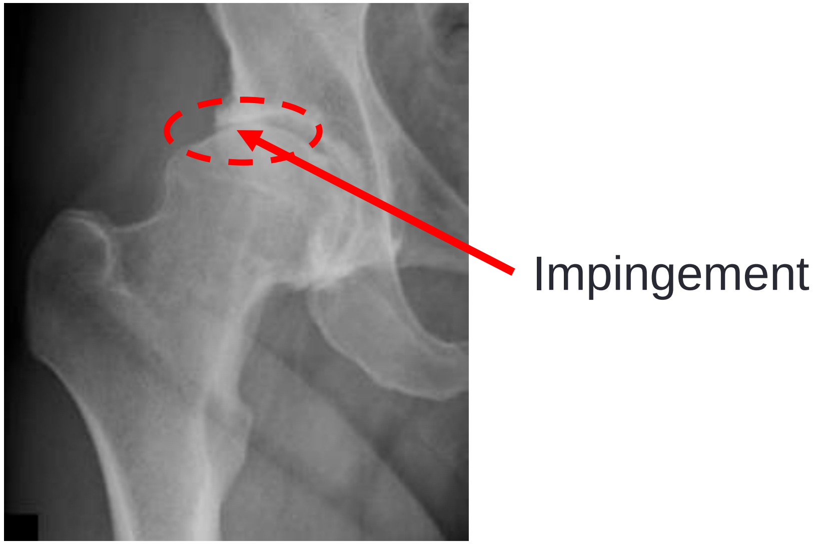
$$\alpha = \arctan(H_x / H_y)$$

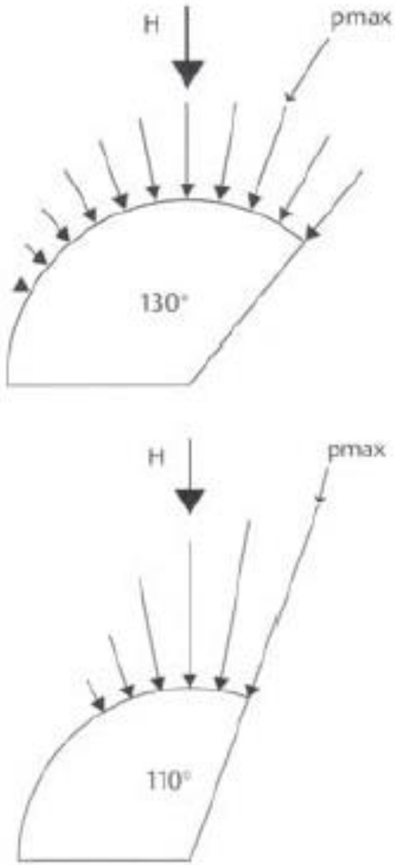
$$\beta = 15°$$

$$\Rightarrow H = 2{,}42 \cdot m \cdot g$$

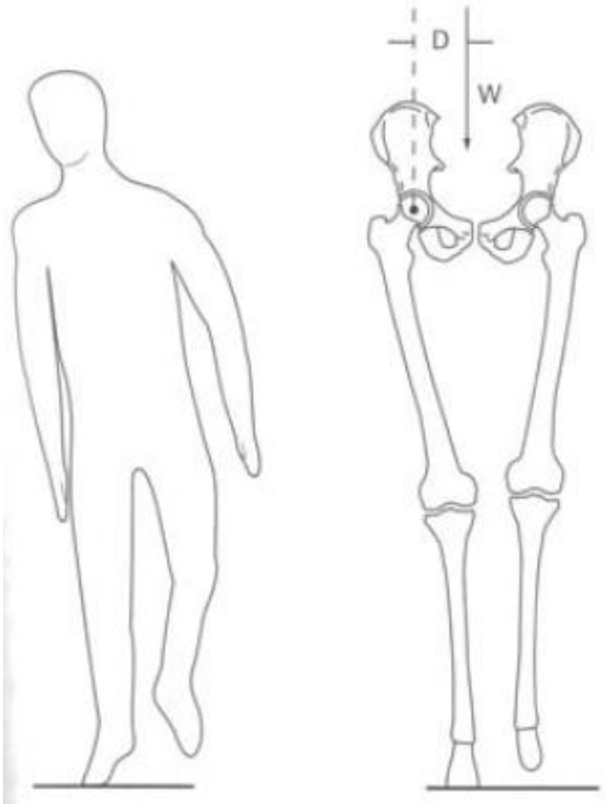
$$\Rightarrow \alpha = 10{,}2°$$

# Hip dysplasia/ Impingement



# Duchenne limping



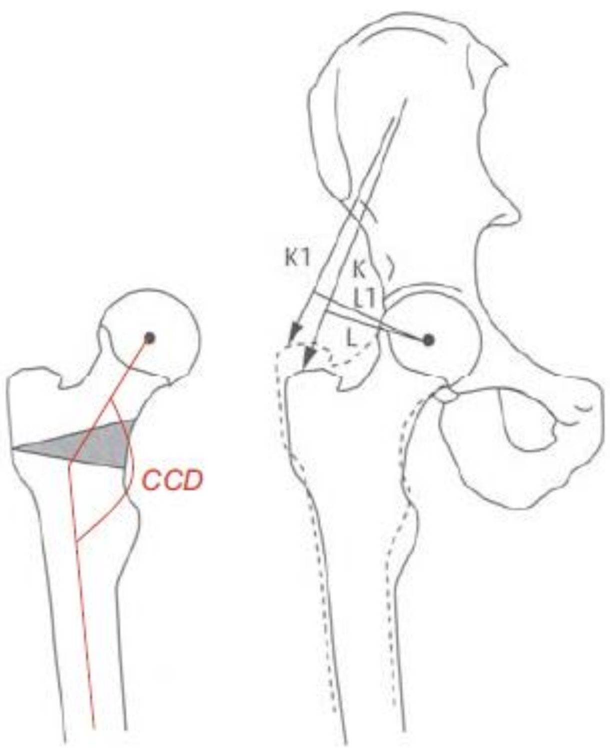

Reduction of distance axis D

Reduction of muscle force K

Reduction of joint force H

BUT:
No long-term solution

# Osteotomy




$$\Sigma M_i = 0 = K_y = (WD)/L_1$$

$$L_1 > L \Rightarrow K_1 < K$$

# Summary

Hip joint is a spheroidal joint between hip and femur

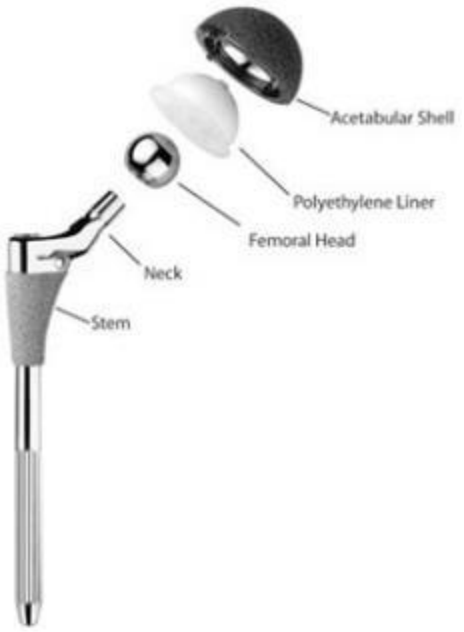
Permanent loading with up to 10 body weight

Already 2D Biomechanics (statics) can help to understand basic principles

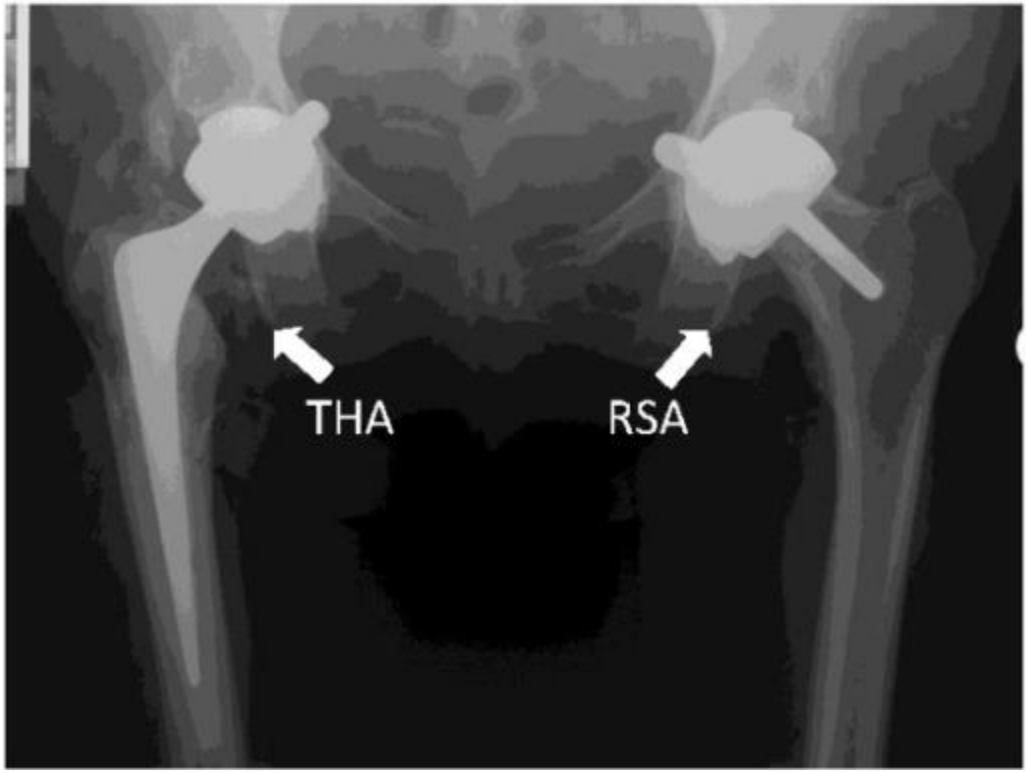
# Questions?

# Hip replacement

- Causes: Trauma, osteoporosis, osteoarthritis, dysplasia
- First surgery in 1891
- Nowadays design based on 1962 (John Charnley)
- High incidence rate 2.5 Mio in 2010 in US (1% of population)
- “Routine” surgery with costs of ~ 10k€

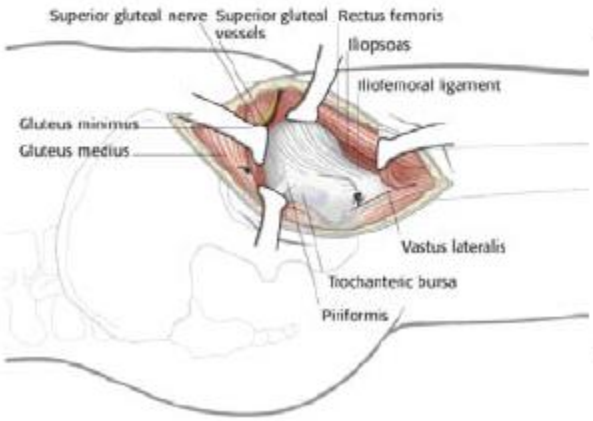


# THA/Hemiprosthesis

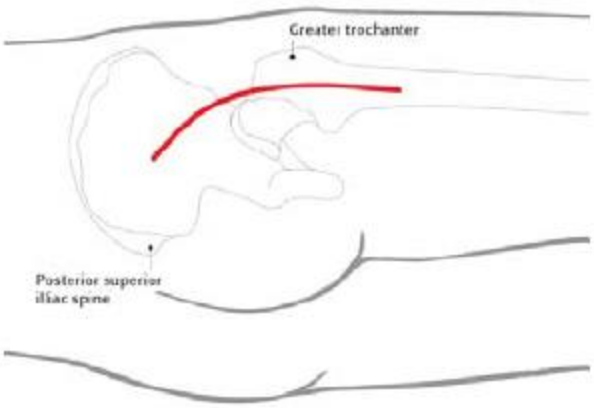



Total Hip Arthroplasty and Resurfacing Arthroplasty

# Surgical procedure - Approach



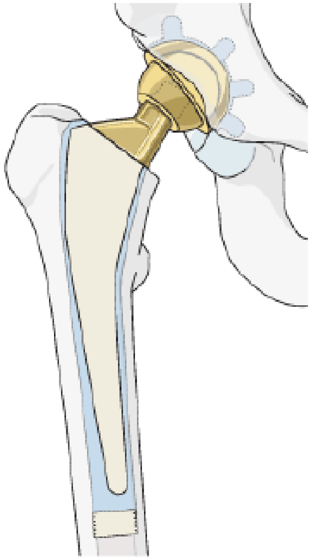

lateral

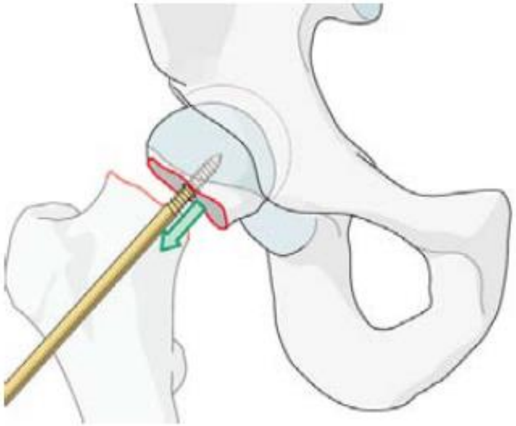



posterior

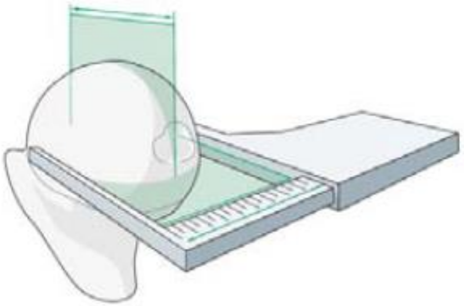
There also exists antero-laterial, anterior, minimally invasive. Depending on surgeons' preferences and experience. No clear best choice.

# Surgical procedure – Femoral head removal



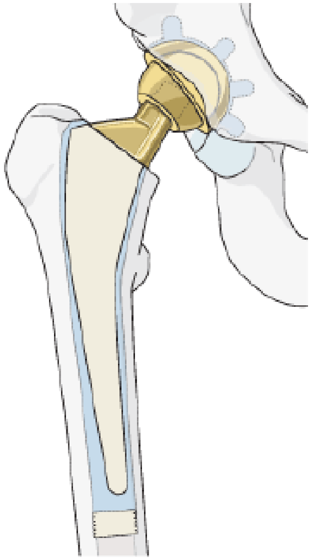


Removal

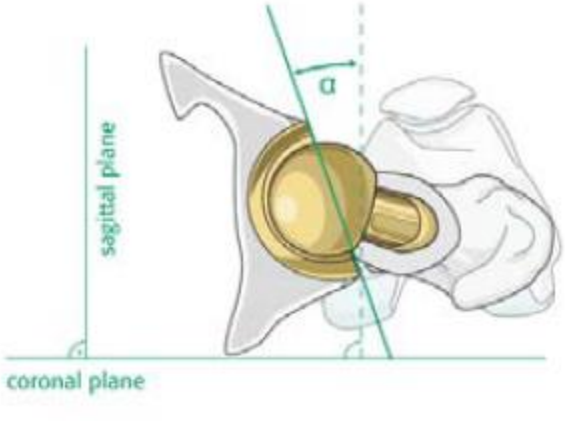


Measurement (if necessary)

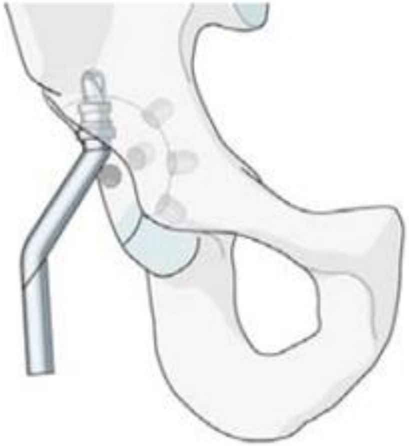
# Surgical procedure – Acetabular component



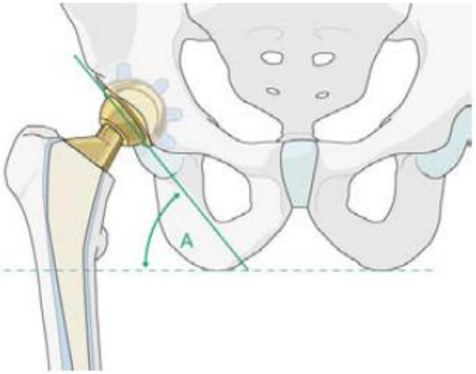
Reaming




Ante version 15°

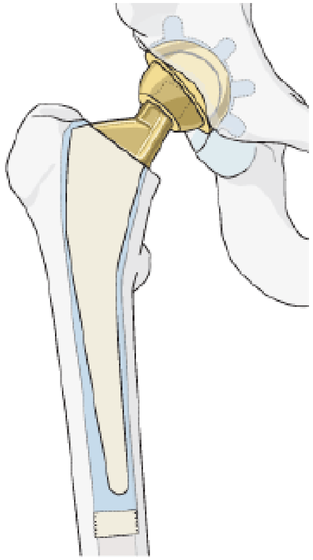


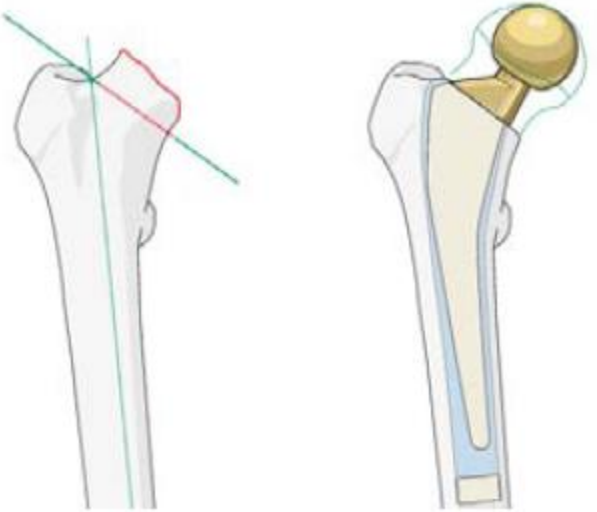
Fixation of acetabular cup

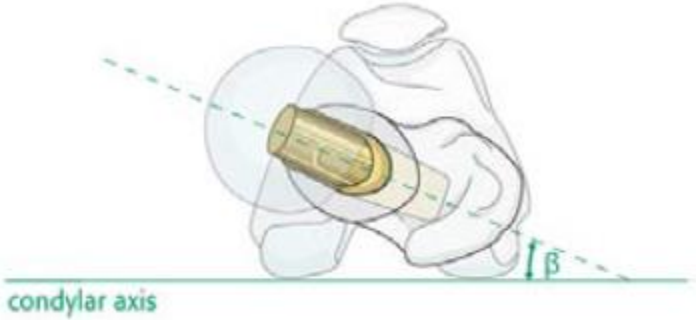



Inclination 45°

# Surgical procedure – Stem insertion



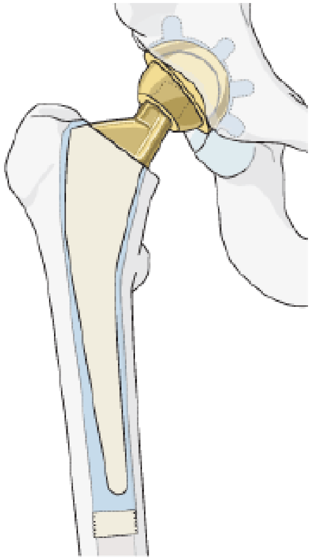


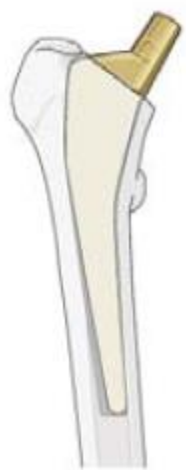



Coaxiality with femur head!

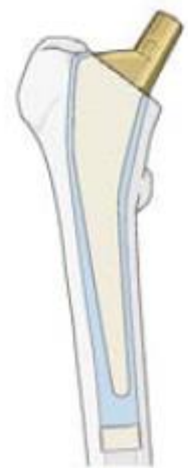
Two fixation possibilities

# Surgical procedure - Fixation





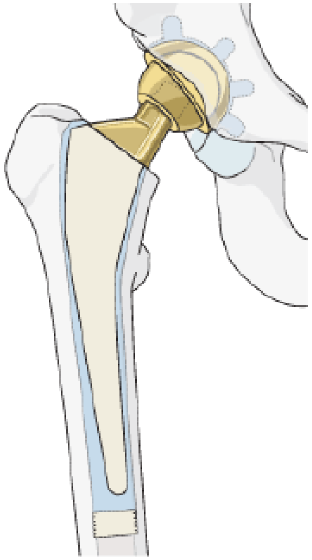
Uncemented – bone ingrowth
For younger patients and/or healthy bones

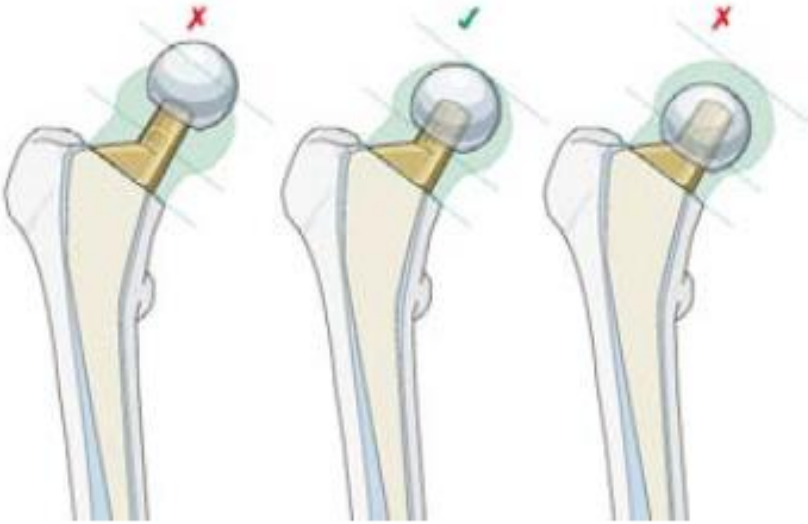


Bone cement – connection with bone. Revision surgery difficult

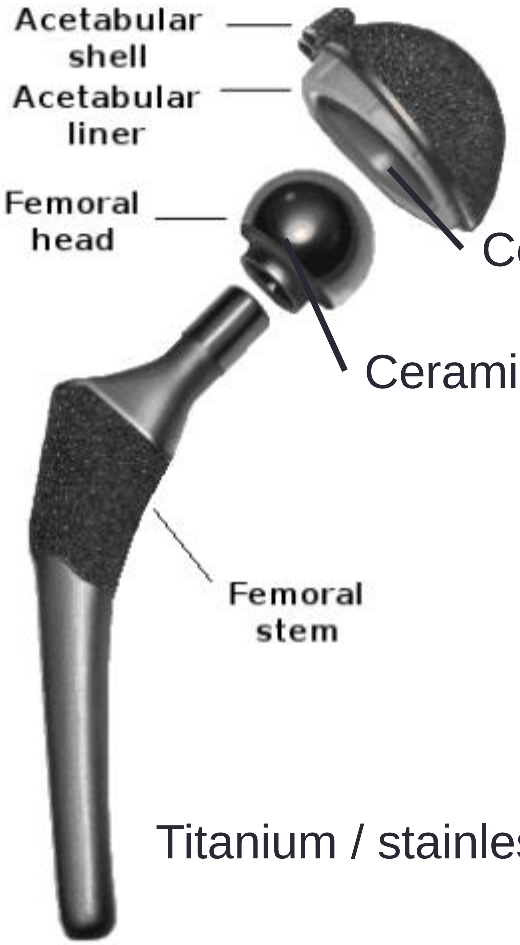
Revision? Hip prosthesis last around 15-20 years in best case scenario

# Surgical procedure – Femoral head





# Materials




Titanium / stainless steel

Ceramic/Metal/Polymer

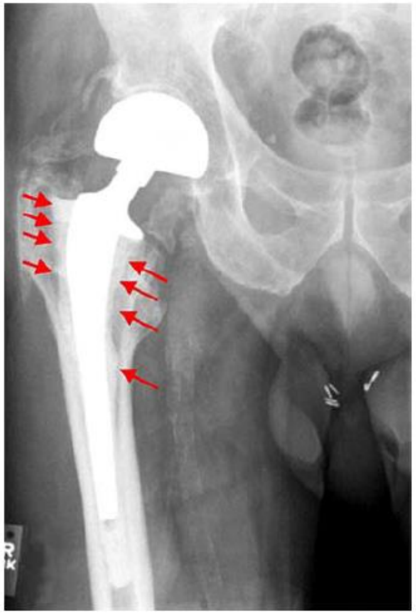
Ceramic/Metal

Titanium / stainless steel

hard-on-hard and hard-on-soft bearings (MoP,MoM,CoM etc.)

Tribology, material-body-interactions, durability ➔ Material engineering

# Challenges and Complications (related to Biomechanics)



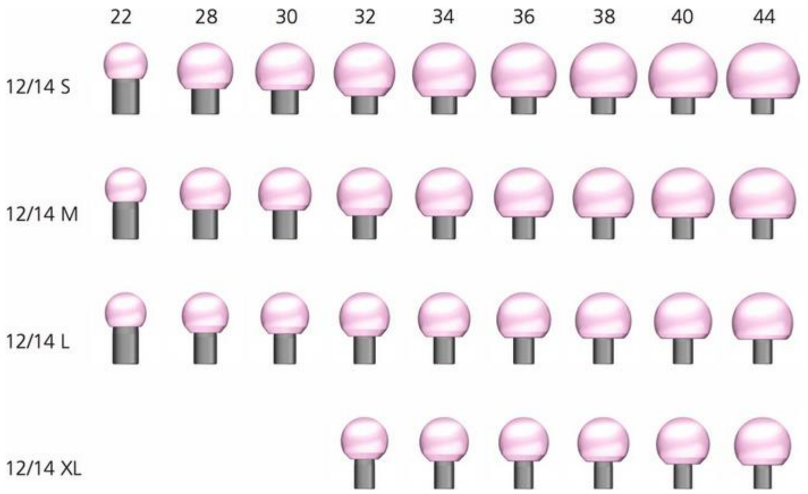
**Loosening**
Material and cement wear

**Dislocation**
Biomechanics and wear

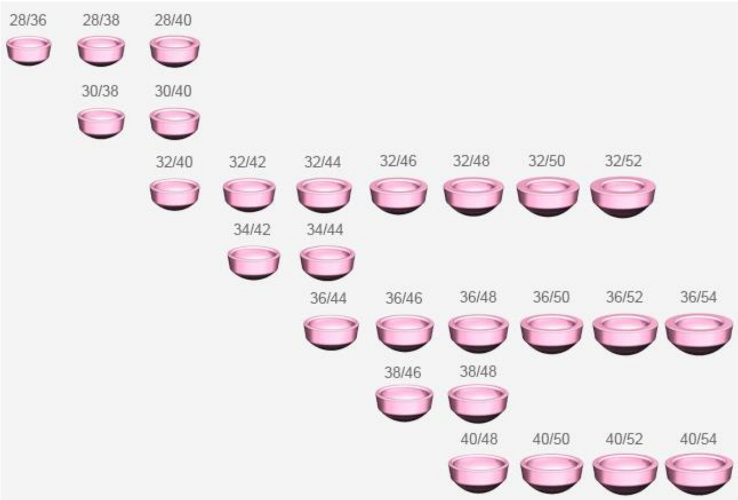
**Fracture**
Oscillatory loading

# Choice of prosthesis

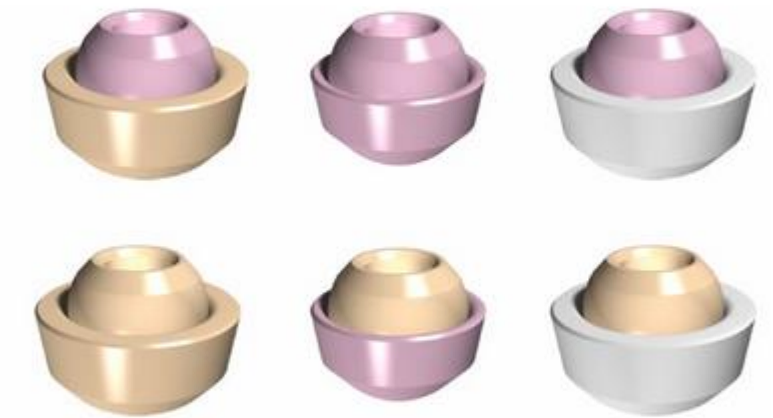
Stem choice




Ball head choice

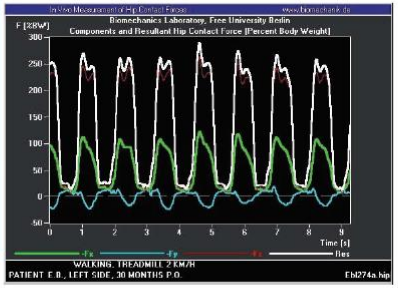



Cup choice

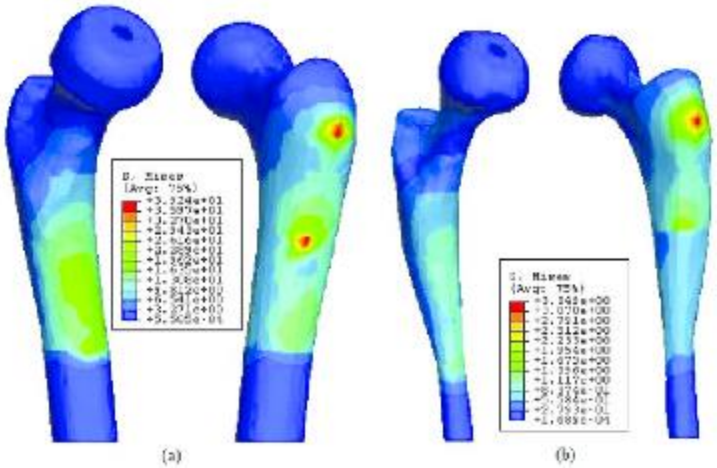


Material pairing choice

# Pre-surgical planning and biomechanical analyses


Bergman et al. 2007




Cilingir et al. 2007

**More in practical courses**

# Video of THA surgery

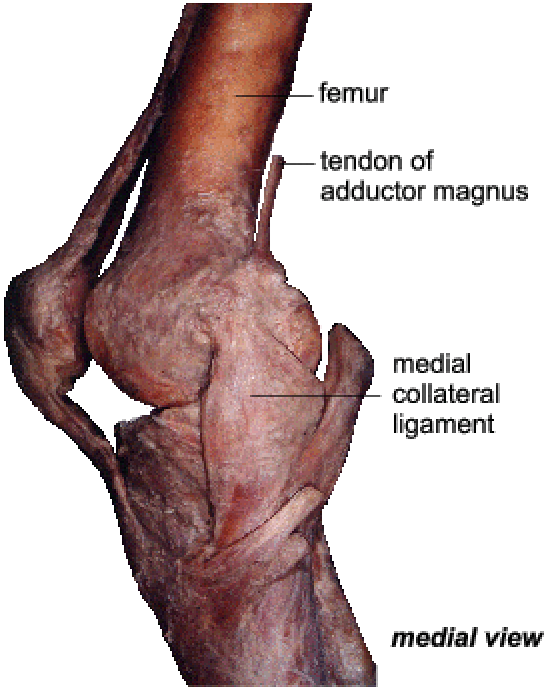
https://www.youtube.com/watch?v=LMLvy-q5rnM&t=211s

95 % success rate, patient mobility 24h after surgery, complete recovery and **drastic** improvement to pre-surgical state

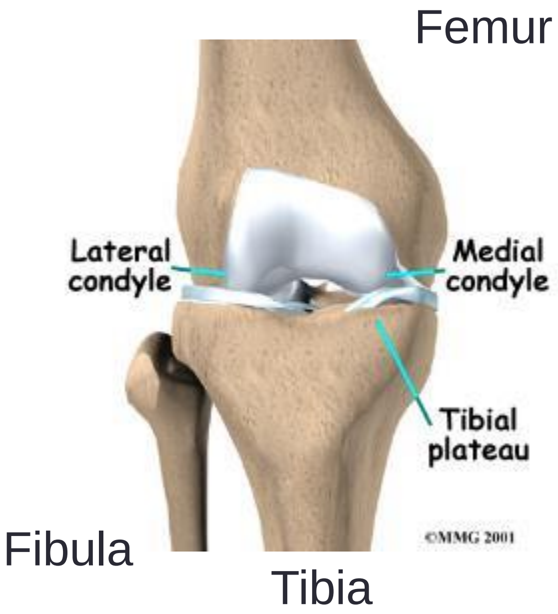
# Questions?

# Knee anatomy

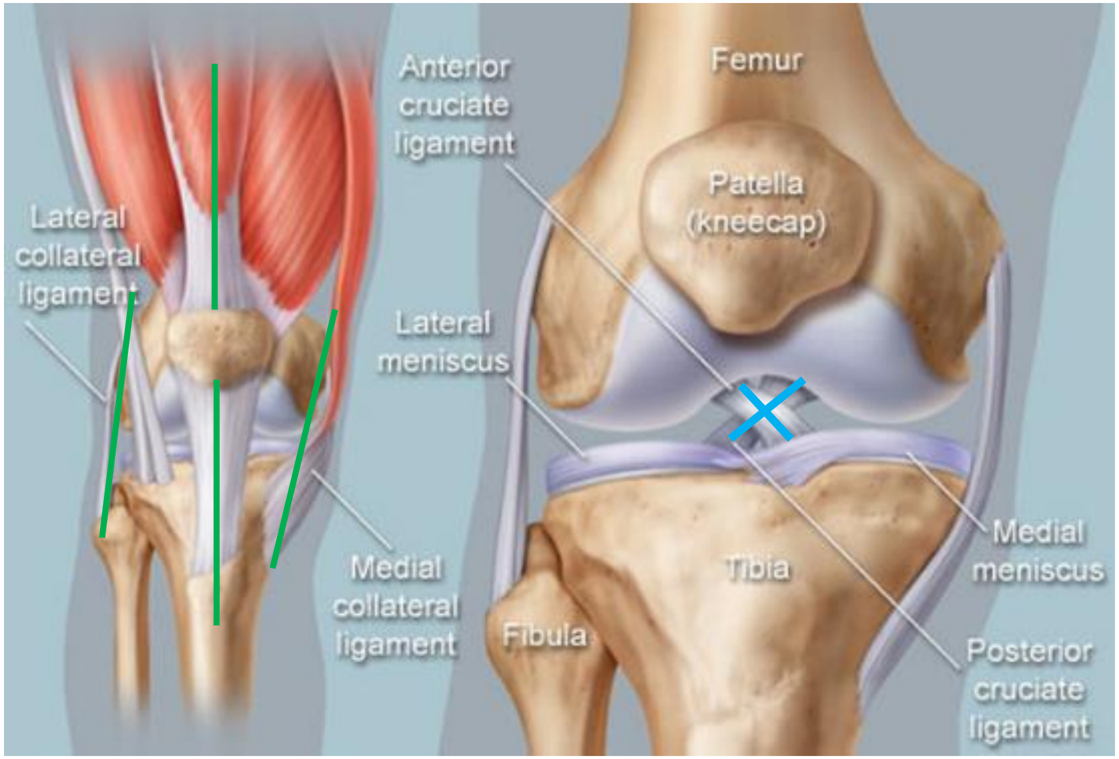
# Tibiofemoral and patellofemoral joint

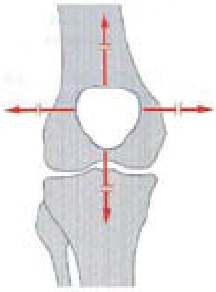



Patella



# Ligaments

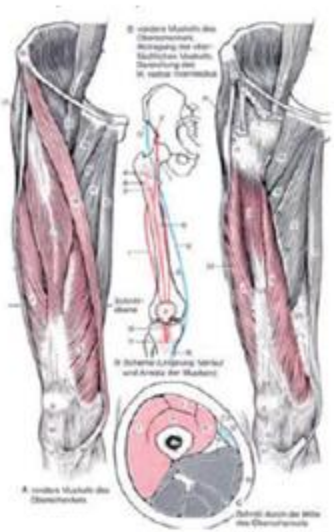


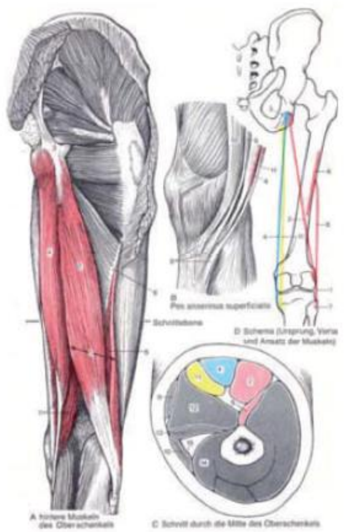
Fixation of patella
Stability of joint

Stability of relative movement between femur and tibia

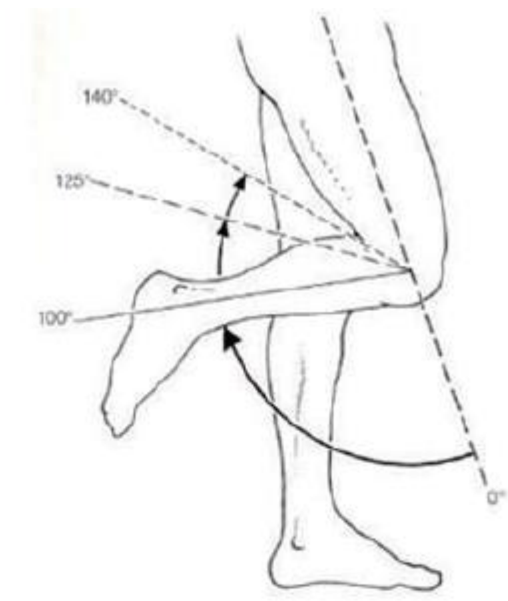
# Muscles and Movement



Flexors



Extensors

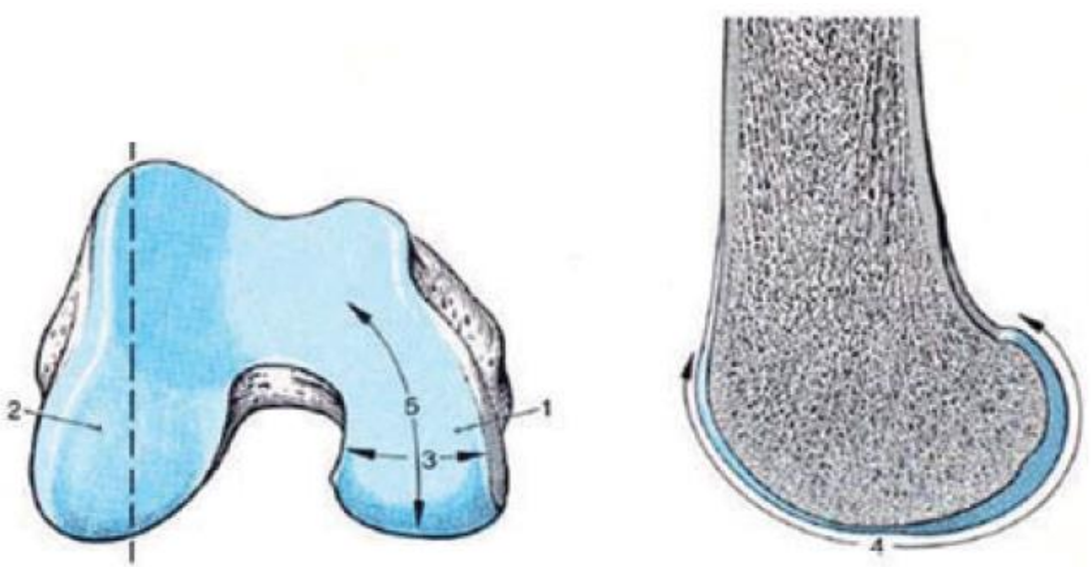



Depends on hip joint: 120-140°

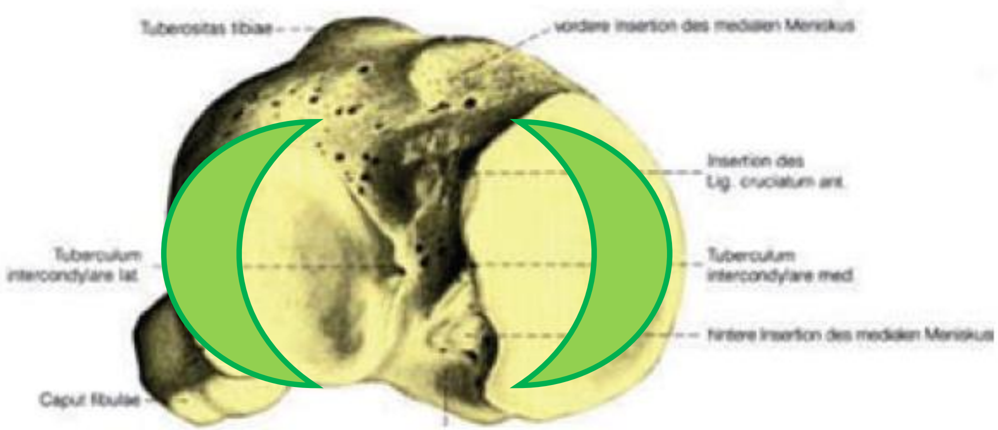
Rotation: -10-30°

# Incongruence in femurotibular joint

Femur



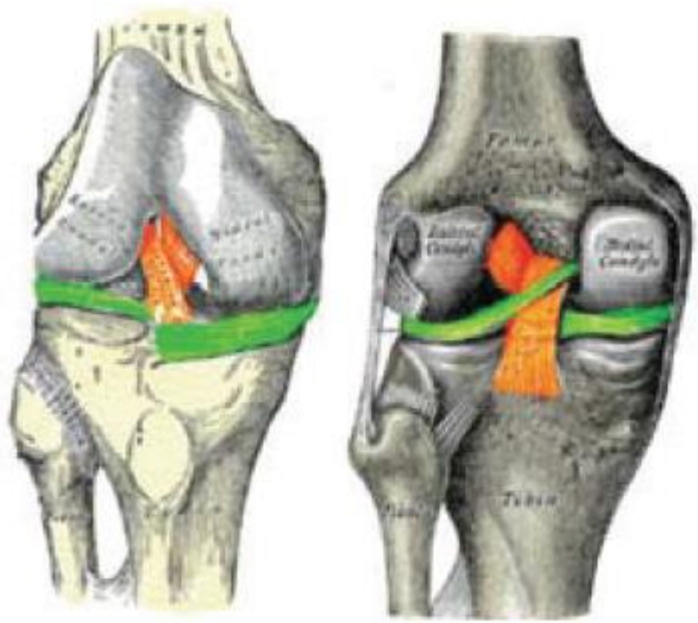

Tibia

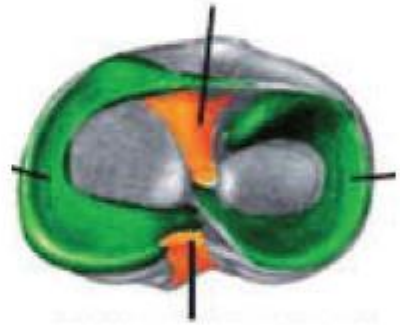


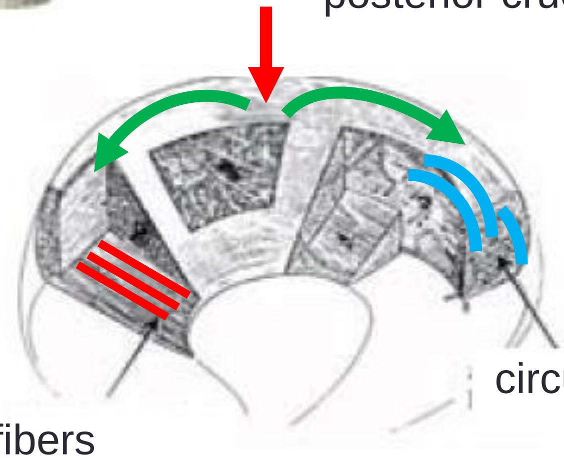

2 Menisci
increase the contact
area by factor of **3!**

Pressure is reduced from
6 to 2 MPa.

# Meniscus




anterior cruciate ligament
medial
meniscus
lateral meniscus
posterior cruciate ligament

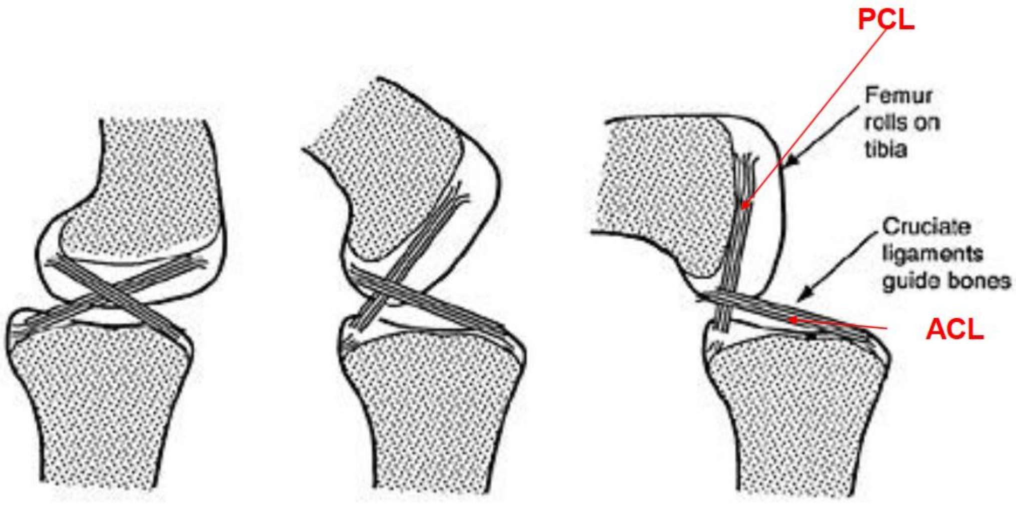

circumferential fibers
radial fibers

# Knee kinematics

https://www.youtube.com/watch?v=H3YgbJLbIXk

# Tibiofemoral joint

https://www.youtube.com/watch?v=Cy-q-16TuX8




A combination of **rolling** and **sliding**
Cruciate ligaments prevent dislocation of joints during movement

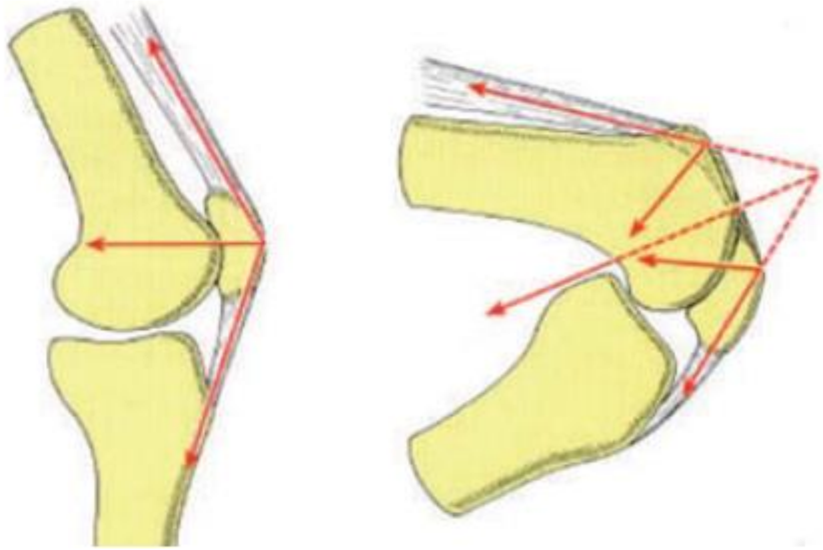
# 4 bar linkage (Menschik 1974)

https://www.youtube.com/watch?v=wWvB3lNYXB0

# Patella kinematics

https://www.youtube.com/watch?v=H3YgbJLbIXk

From 1:30



Translates the force from the quadriceps to the tibia.
Patella force (compression) depends on **bending angle**!

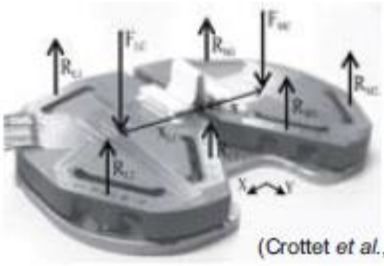
# 4 bar linkage is a simplification

In reality tibiofemoral movement is three dimensional.
Axial rotation between femur and tibia.

⇩

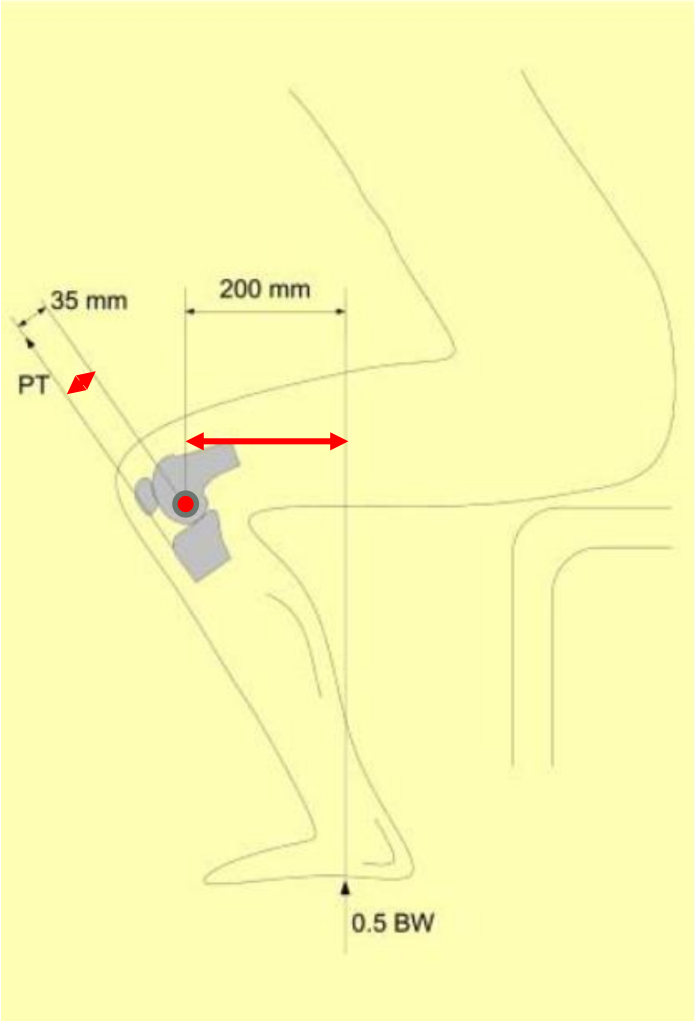
In vivo measurements and more sophisticated modeling is necessary!

(Marmignon *et al.*, 2004)



(Crottet *et al.*, 2005)

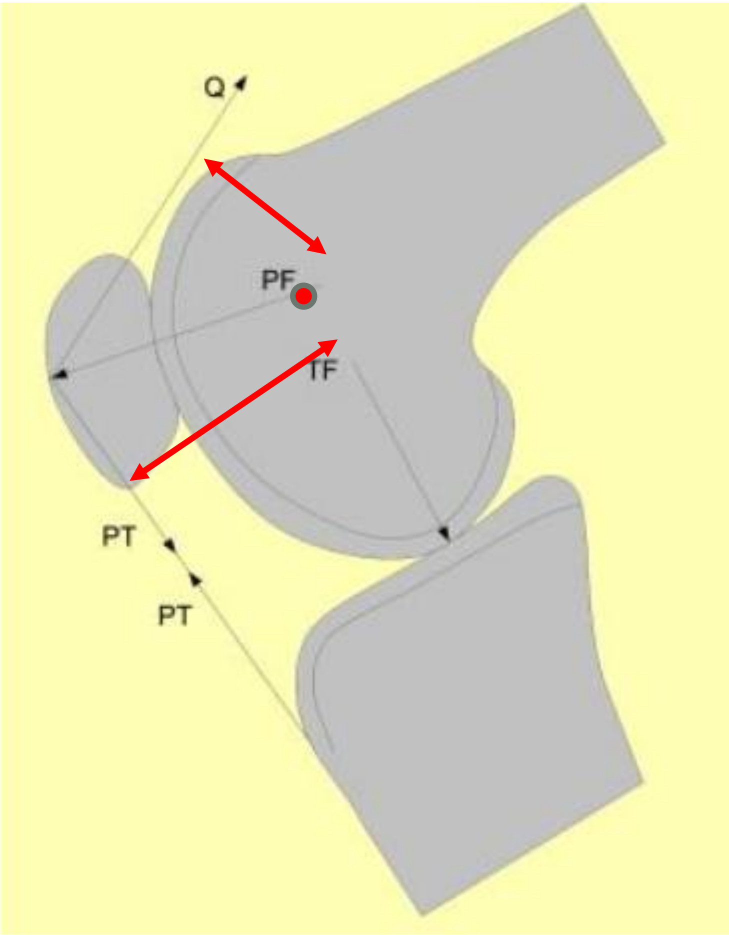
# Forces during rising from chair




$$\Sigma\, M_i = 0 = PT = (0.5BW * 200mm)/35mm$$

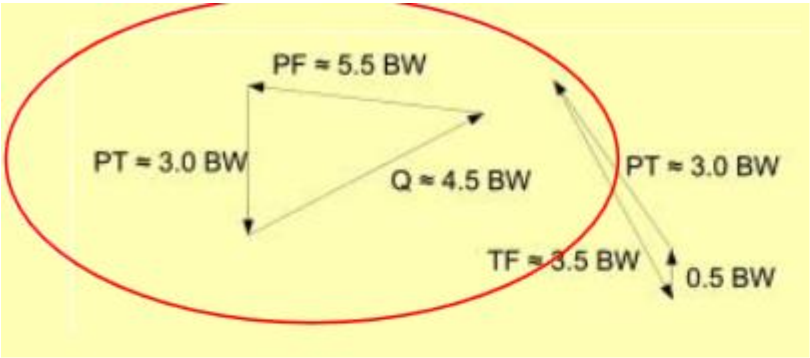
$$PT \approx 3\ BW$$

# Forces during rising from chair



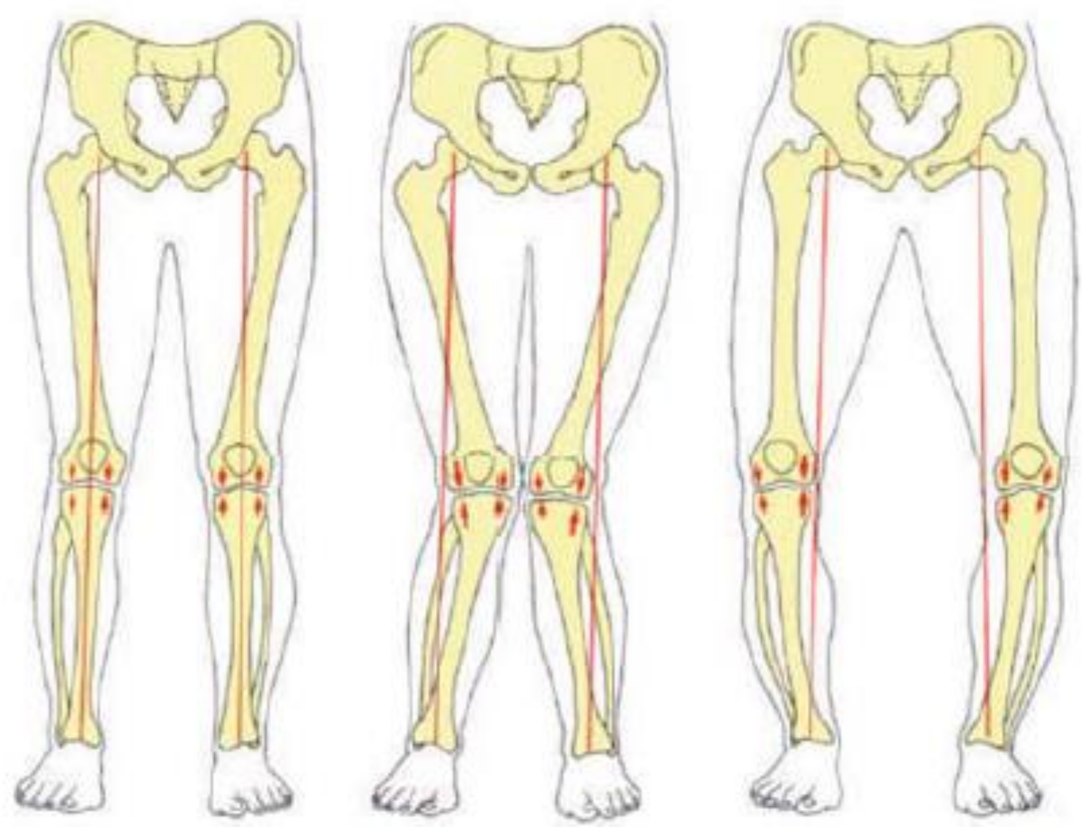

$$\Sigma M_i = 0 = Q = (PT * 35mm)/22mm$$

$$Q \approx 4.5\ BW$$




PF = **5.5** BW!
during squatting
patella force up to **7.6 BW**!

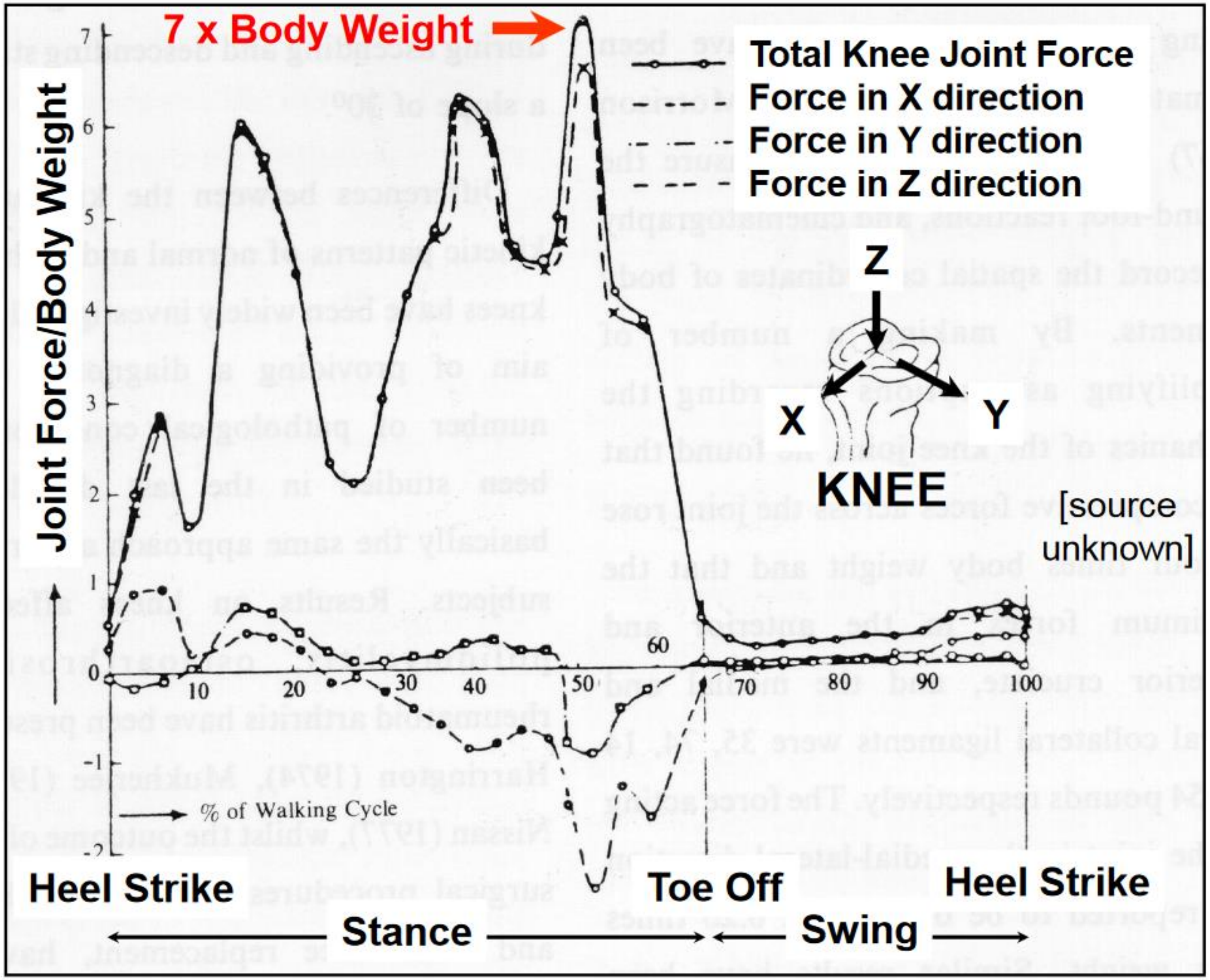
# Forces increase in pathologies



Normal Valgus Varus

Self-intensifying deformities!

# The walking cycle



# Summary

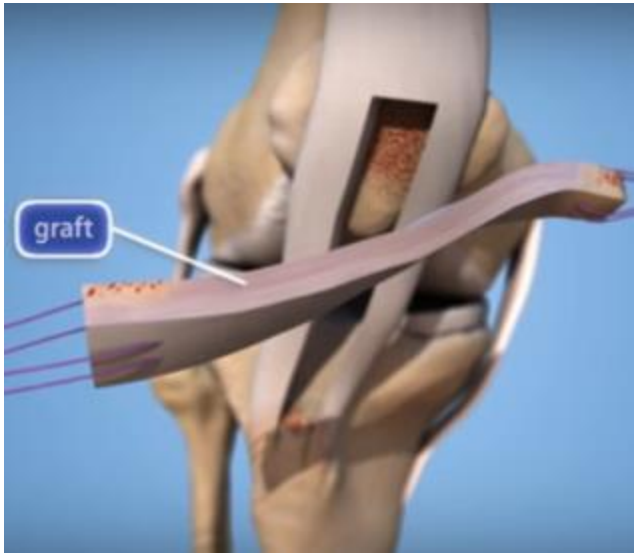
- Knee is one of the most complicated joints in the body
- Rolling, sliding and rotational movement (3D)
- High forces (7 BW in walking)
- Ligaments and menisci play a **crucial** role in biomechanics
- Injuries of soft tissues may evolve in **severe** pathologies

# Questions?

# Pathologies & Therapies - Ligament rupture

ACL/PCL very common in competitive disciplines

**Autograft tendon reconstruction surgery**

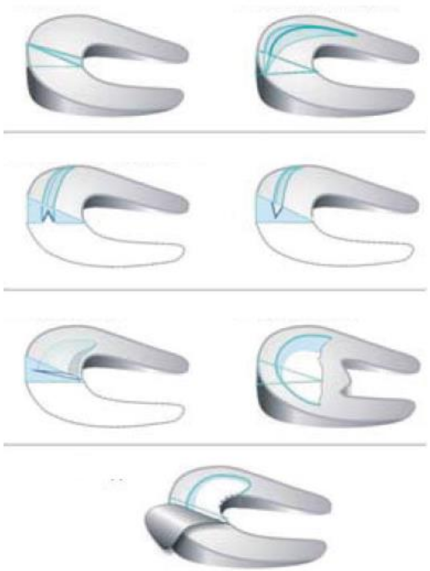



# Pathologies & Therapies – Meniscus rupture

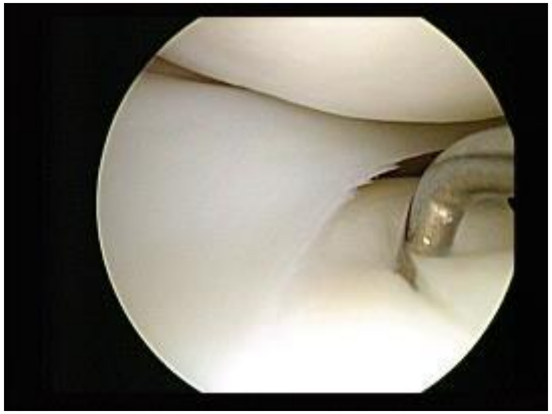
Many locations possible

Treatment via arthroscopy

Meniscus replacement under investigation



Meniscus rupture



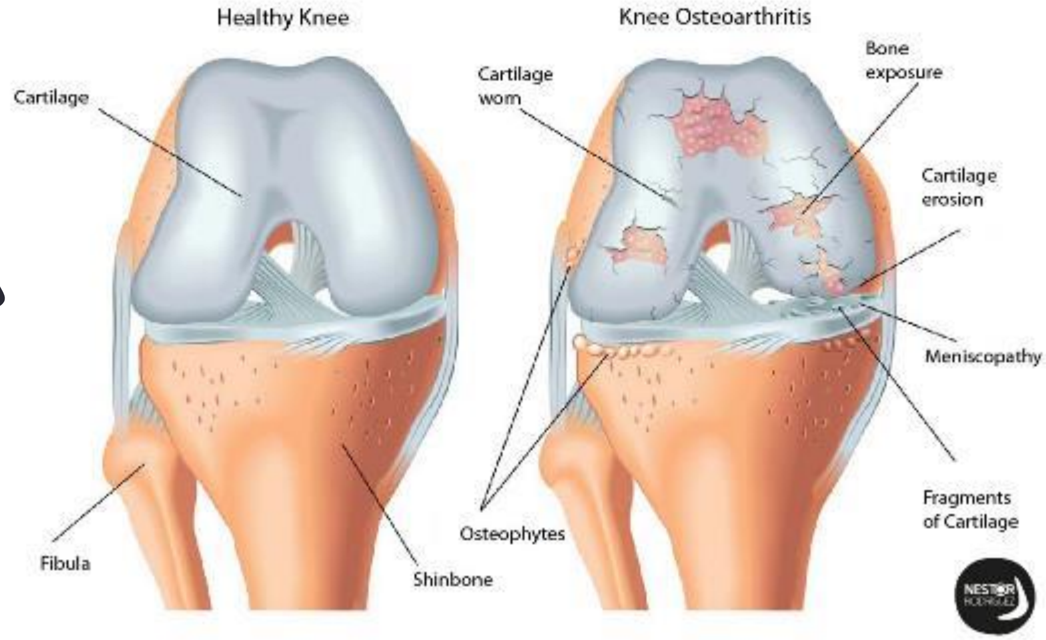
Arthroscopy

# Pathologies & Therapies - Osteoarthritis

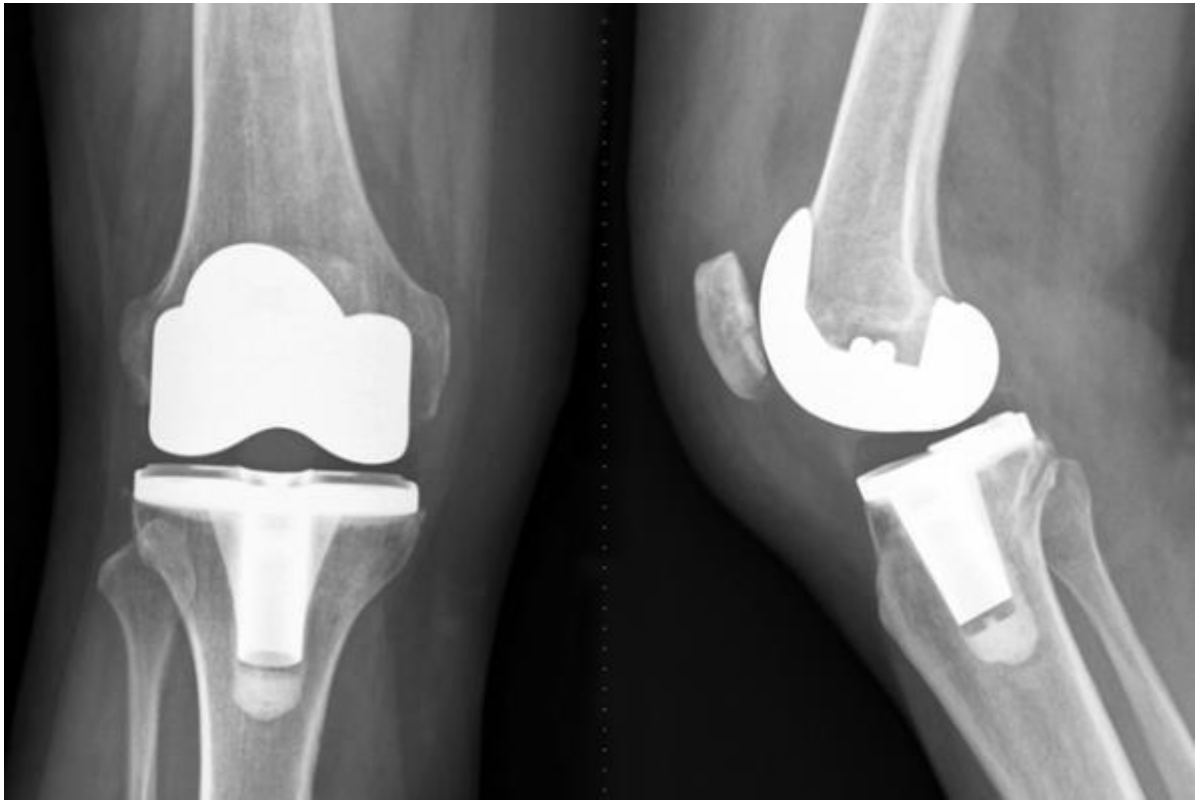
Irreversible cartilage destruction ➔ pain, low movement, joint dysfunction

High prevalence, 4 Mio in US with end-stage disease (➔total knee replacement)
Estimated risk of 7-10% being in need of TKR throughout life

**Tissue Engineering Lecture (L5)**



# Total Knee Replacement



Analogous to THA – Replacement of both joint surfaces (Femur&Tibia)

# Animation of procedure (after bone preparation)

https://www.youtube.com/watch?v=DXXPKWCBqYk

Surgery Video

https://www.youtube.com/watch?v=H9NrKylKMIY

95% success rate with duration up to 10-15 years
Long rehabilitation (3 months) – invasive surgery
Complications similar to hip endoprosthesis (“bad” biomechanics)

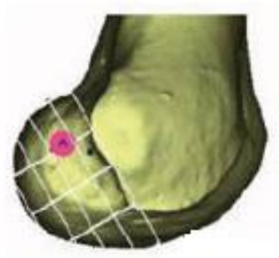
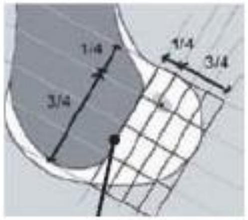
# Many designs possible

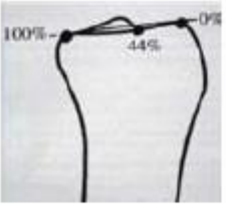

Standard design

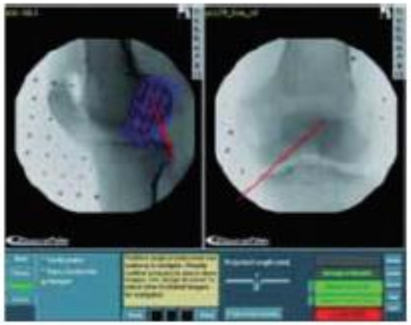

High movement


Bone ingrowth

# Research ongoing



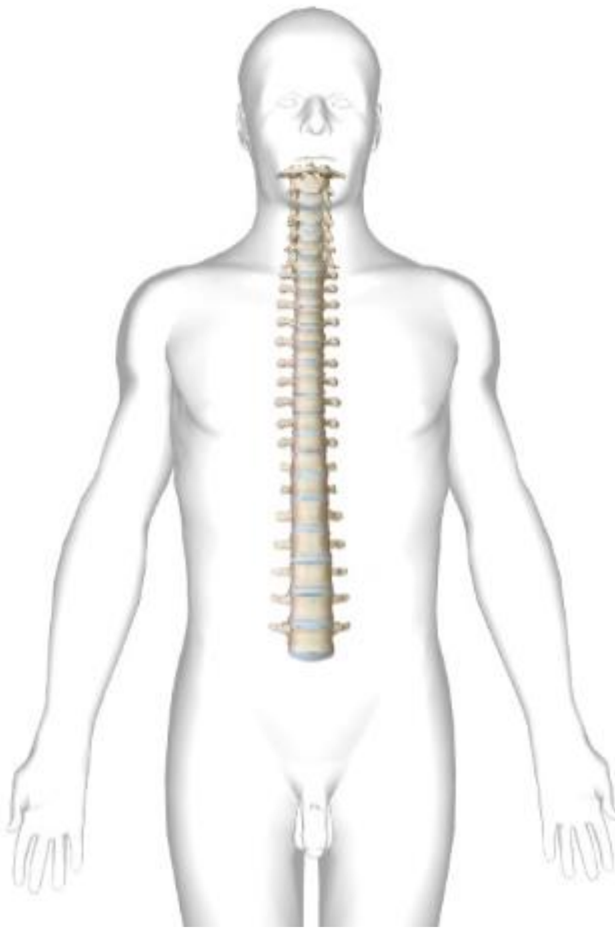

**Computer-supported implant planning and guided surgery**

Biomechanics of joint loading

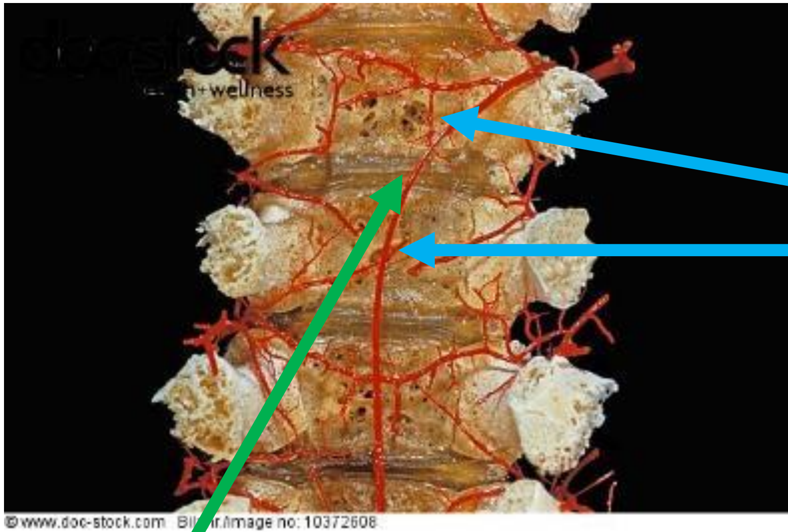
New materials and implant designs...

# Questions?

# Spine anatomy

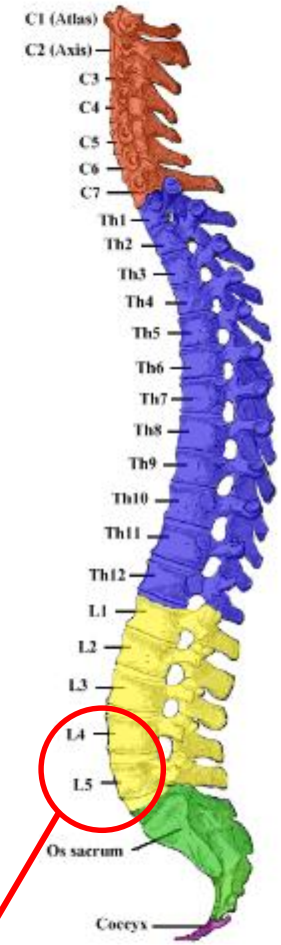
# Vertebral joint



Vertebrae

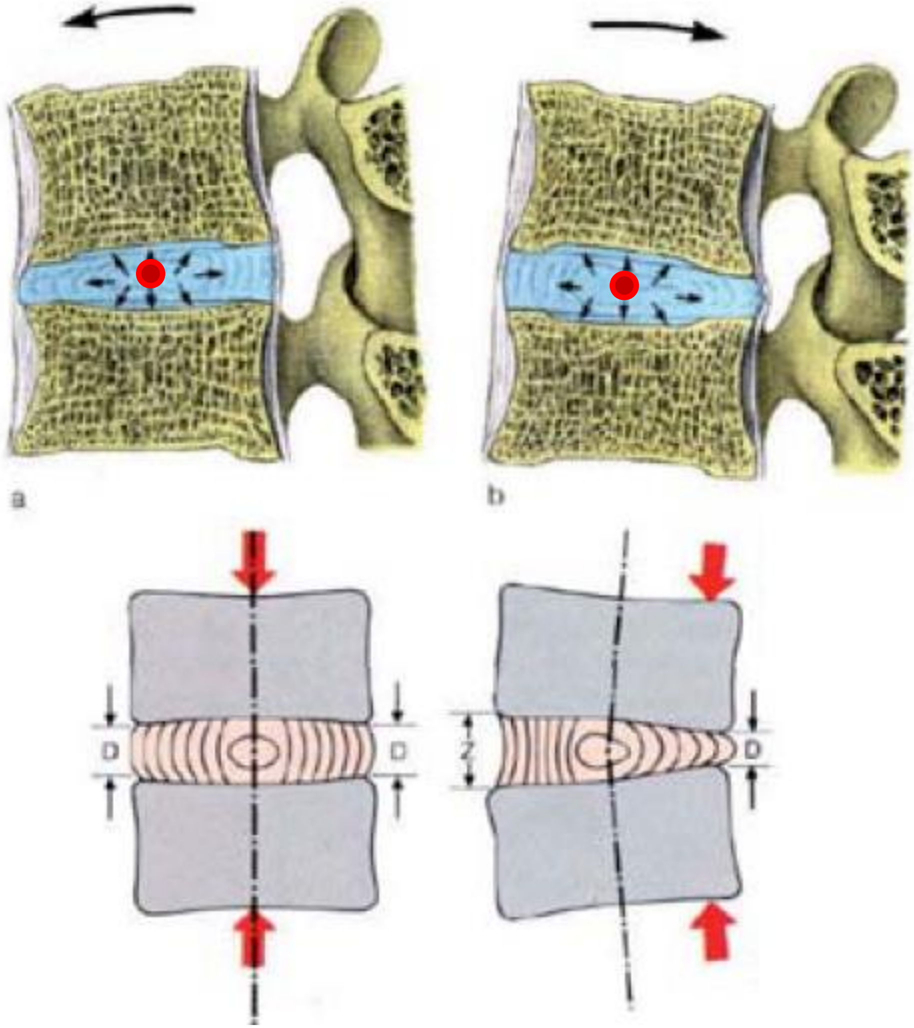
Intervertebral disc

4 regions
Stabilization of body and shock absorbance
**Two Vertebrae** and **one intervertebral disc** create one functional unit




Problems most often with L4 and L5

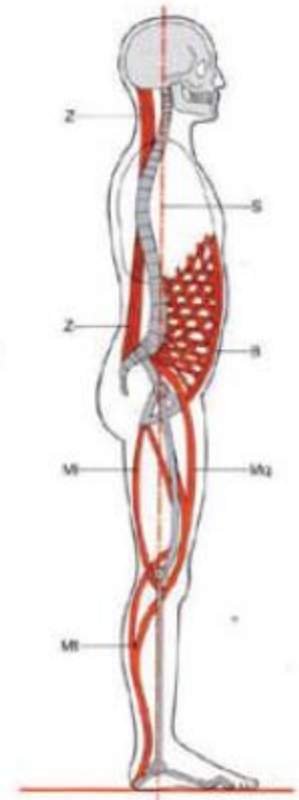
# Joint kinematics



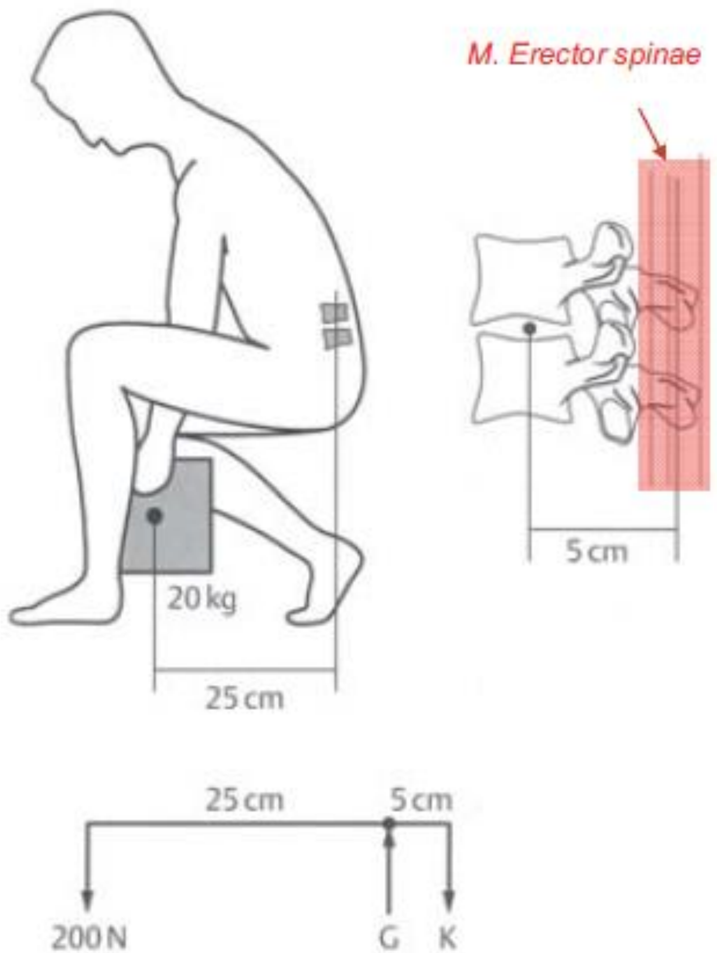

Center of rotation approx. in center of disc

+/-10° flexion/extension

Spinal muscles and abdominal muscles involved



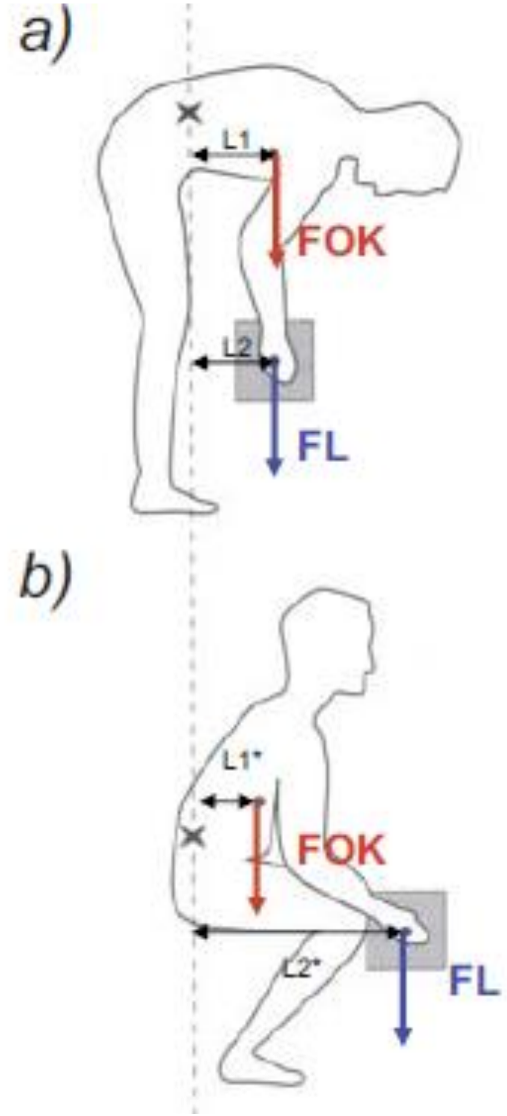
# Joint stresses during 20 kg lift




In vivo (dynamic case) much higher
4000-6000N ➔ 2.3 MPa (car tire 0.2 MPa)

$$\sum M = 0 = -K \cdot 5 + 200 \cdot 25$$
$$\Rightarrow K = 1000[N]$$
$$\sum F = 0 = G - 200 - K$$
$$\Rightarrow G = 1200[N]$$

# Lifting strategy

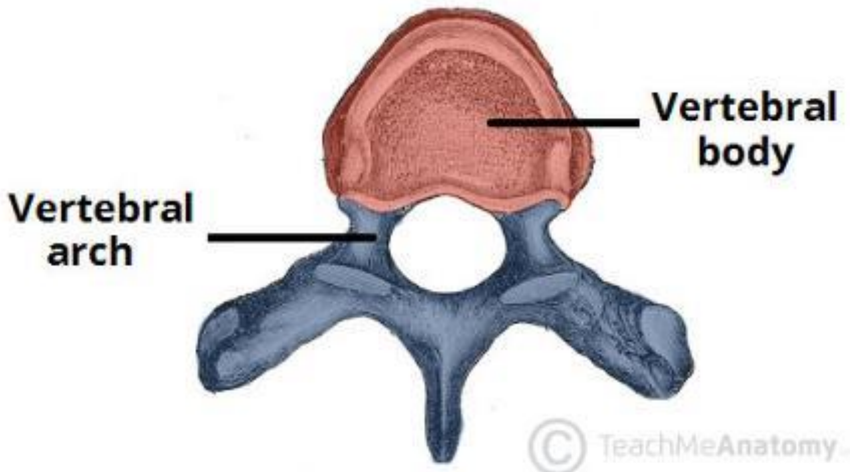


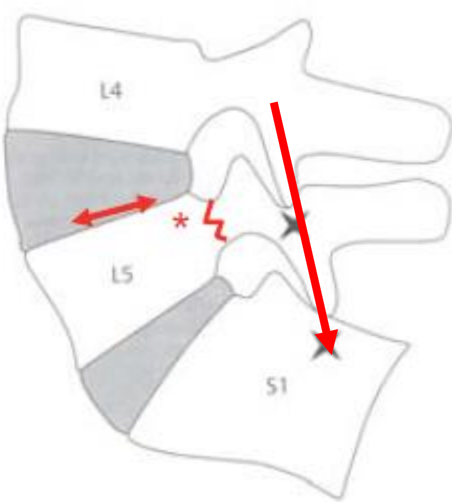

Compression of vertebral discs minimal

a) if FL>>FOK (heavy weight, light person)

b) if FL < FOK (heavy person, light weight)
Stress in knee joints!

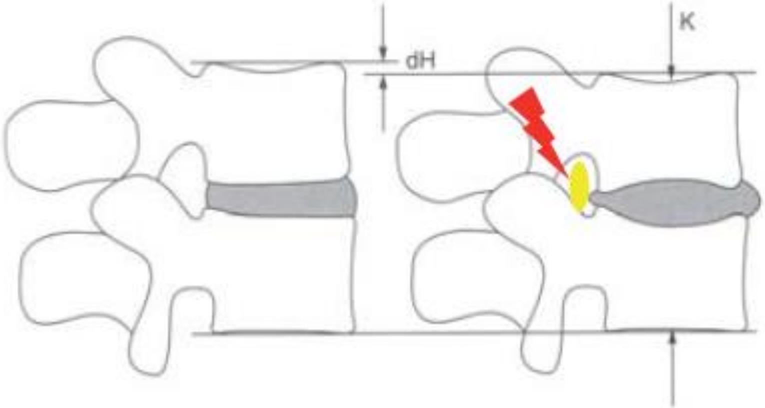
# Pathologies – Fracture of vertebral arch



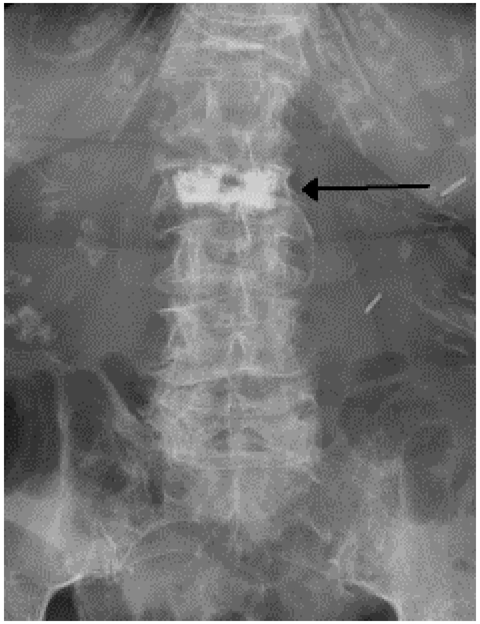

Bone stiffness much higher than vertebral disc and tendon/muscle stiffness ➔ force translated through bones ➔ Fracture possible

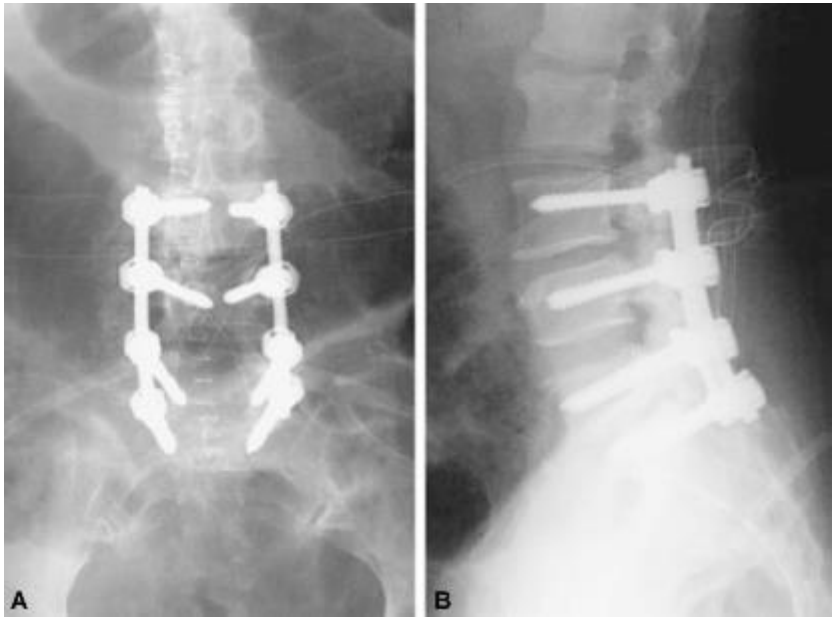
# Spinal disc herniation




Age related material degradation and axial stresses lead to irreversible material deformation and tear ➔ reduction of function, inflammation, back pain

# Treatment options






**Kyphoplasty/Vertebroplasty:**
Injection of cement to reduce compression of verebrae

**Spinal fusion:**
Connection and stabilization of several vertebrae

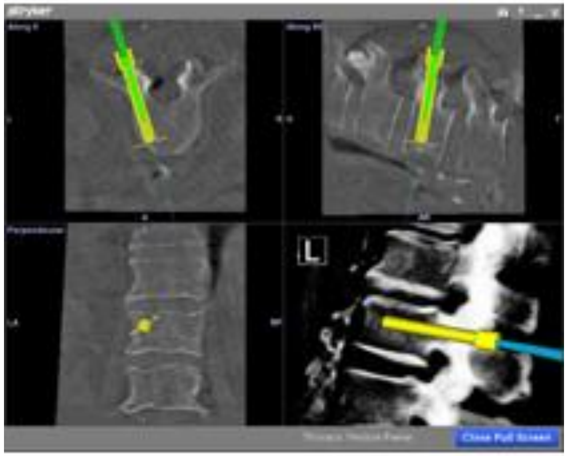
# Vertebral prosthesis

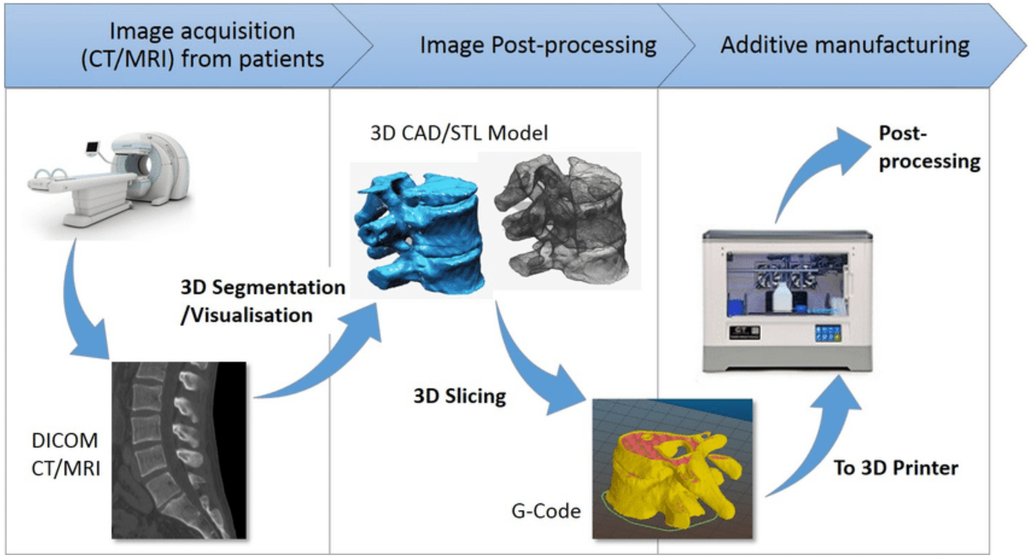
# Research outlook

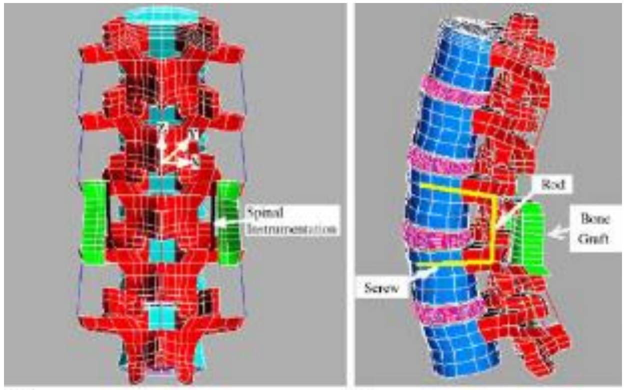
Computer guided surgery

Patient specific implants

FEM studies






(a) (b)

# Questions?

# Summary

- Bones, muscles, tendons, ligaments and cartilage are important players of each joint. Each with own function and biomechanical properties
- Damage affects biomechanics of joint with self-intensifying consequences
- Age-related material degradation (esp. **cartilage**) results in necessity of joint replacement
- Surgeries in combination with rehabilitation allow function of implants for 15-20 years
- Future steps take patient-specificity, minimal invasiveness and computer-guided surgery into consideration

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